The Belle experiment at KEK accumulated a $121.4\,\text{fb}^{-1}$ sample of $e^+e^-$ collisions at the $\Upsilon(5S)$ resonance. This sample provides ample opportunity for improving the understanding of both the properties of $B_s$ mesons and the spectroscopy of bottomonium states. In this article we describe the recent results obtained from the Belle $\Upsilon(5S)$ data.
1 Introduction

The story of Υ(5S) measurements began in 1985 when the CLEO and CUSB collaborations reported the first “observation of a new structure in the $e^+e^−$ cross section above the $\Upsilon(4S)$”, with 0.1 fb$^{-1}$ of data collected at the Cornell Electron Storage Ring.\cite{1, 2} The observed Υ(5S) resonance is a bottomonium state (quark content $b\bar{b}$) with a mass of $(10876\pm11)$ MeV/c$^2$ and a width of $(55\pm28)$ MeV/c$^2$.\cite{3} In the ensuing two decades, CLEO and the $e^+e^−$ B-factory experiments, Belle and BaBar at KEKB (Tsukuba, Japan) and PEPII (Stanford, US), focussed on taking data at energies near the mass of the $\Upsilon(4S)$ resonance, which is just above the kinematic threshold for pair production of $B^0\bar{B}^0$ and $B^+B^−$ pairs and therefore provides an ideal environment to study the decays of these mesons. The heavier $B_s$ mesons cannot be produced at $\Upsilon(4S)$, but it is possible at higher collision energies. It was in 2003 when a larger $\Upsilon(5S)$ data sample of 0.42 fb$^{-1}$ was collected by the CLEO III detector. Analysis of this data led to the first evidence for $B_s$ production at the $\Upsilon(5S)$ energy.\cite{4, 5} This sparked interest in the $\Upsilon(5S)$ resonance at the Belle experiment and the first 23.6 fb$^{-1}$ data sample was collected from 2005 to 2006 and then extended to a total integrated luminosity of 121.4 fb$^{-1}$ collected from 2008 to 2009. Belle’s $\Upsilon(5S)$ data sample is by far the largest to date, and all results in this review are obtained from it.

While the main goal of the $\Upsilon(5S)$ physics program was to study the decays of the $B_s$ meson, it turned out that Belle’s large data sample is also an ideal base to study the bottomonium spectrum and to discover unexpected states. We structure this review in two parts: in the first part, we discuss the $B_s$ measurements, and in the second, the spectroscopy of conventional and unconventional bottomonium states.

Before presenting the results, we clarify some of the terminology used throughout this review. What is commonly considered as the $\Upsilon(5S)$ peak in the $e^+e^−$ hadronic cross section might contain a contribution from a neighbouring $Y_b$ state which is discussed in Sec. 3.3.3. Besides the resonant process $e^+e^− \rightarrow \Upsilon(5S)$ and possibly $e^+e^− \rightarrow Y_b$, the hadronic cross section contains the so-called continuum processes $e^+e^− \rightarrow q\bar{q}$, with $q = u, d, s, c, b$. In the literature the label “$\Upsilon(5S)$” is used for the whole bottom production near the $\Upsilon(5S)$ mass peak, including all resonant and non-resonant processes – in other words for everything but the $q\bar{q}$ continuum involving quarks lighter than the $b$-quark ($q = u, d, s, c$). We will follow this convention in this article.

2 $B_s$ Measurements

The $B$-factory experiments Belle and BaBar can look back on a veritable success story. Their measurements of $B^0$ and $B^+$ meson decays significantly improved our understanding of $CP$ violation and quark flavor transitions described by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism.\cite{6, 7} The knowledge of $B_s$ decays was, however, rather sparse until recently when Belle started pioneering the investigation of $B_s$ mesons using the $\Upsilon(5S)$ data sample. Shortly after, the experiments at the Large Hadron Collider (LHC) located near Geneva followed, in particular the dedicated $B$-physics experiment
LHCb. The LHC experiments profit from an enormously high $B_s$ production cross section, $\sigma(pp \to B_s X) = (0.105 \pm 0.013) \times 10^5$ nb, at $\sqrt{s} = 7$ TeV in $pp$-collisions,\textsuperscript{8} compared to $\sigma(e^+e^- \to B_s X) = (0.12 \pm 0.02)$ nb at the $\Upsilon(5S)$ resonance.\textsuperscript{9} However, studying $B_s$ decays at an $e^+e^-$ B-factory has certain advantages over measurements at a hadron collider. Firstly, the number of produced $b$-flavored mesons is well known and absolute branching fractions can be measured. In contrast to the production at hadron colliders, $B_s$ mesons are produced in $\Upsilon(5S)$ decays coherently in quantum mechanically entangled pairs. Full or partial reconstruction of one of the $B_s$ mesons provides information on the second $B_s$ meson in the event, which is a prerequisite for inclusive analyses, for example the measurement of the $B_s \to X\ell\nu$ branching fraction discussed in Sec. 2.3. A further benefit of an $e^+e^-$ collider is the complete knowledge of the initial state that provides kinematic constraints for the reconstruction of undetected particles such as neutrinos.

The analyses of $B_s$ decays with $\Upsilon(5S)$ data build on the experience of $B^0$ and $B^+$ studies at $\Upsilon(4S)$ by transferring the existing techniques to the higher collision energy. Most $B_s$ analyses performed so far are untagged, i.e. one $B_s$ is fully reconstructed in the signal final state, while the second $B_s$ in the event is not explicitly reconstructed. Correctly reconstructed $B_s$ mesons can be separated from misreconstructed candidates by means of two variables: the beam energy constrained mass, $M_{bc} = \sqrt{s/4-p_B^2}$, and the difference between expected and reconstructed $B_s$ energy, $\Delta E = E_B^* - \sqrt{s/2}$. The variables $p_B^*$ and $E_B^*$ are the reconstructed $B_s$ momentum and energy in the center-of-mass frame of the colliding beams, respectively. In $\Upsilon(4S)$ decays, the $BB$ pairs are produced close to the kinematic threshold, and decay nearly at rest in the $e^+e^-$ rest frame. Correctly reconstructed $B$ candidates have thus $M_{bc}$ around the nominal $B$ mass and $\Delta E$ consistent with zero. The situation is a little different in $\Upsilon(5S)$ decays, where not only the production of $B_s\bar{B}_s$ pairs is kinematically allowed, but also $B^*_s\bar{B}_s$ and $B^*_s\bar{B}^*_s$. The mass difference between $B^*_s$ and $B_s$ is only $48.7^{+2.3}_{-2.1}$ MeV/$c^2$,\textsuperscript{3} thus the photon emitted in the $B^*_s$ decay has too low energy to be efficiently reconstructed. Hence, true $B_s$ candidates populate three distinct regions in the $\Delta E-M_{bc}$ plane depending on whether the $\Upsilon(5S)$ decay was to $B_s\bar{B}_s$, $B^*_s\bar{B}_s$ or $B^*_s\bar{B}^*_s$ (see Fig. 1).

2.1 Estimation of $B_s$ production

The $\Upsilon(5S)$ resonance decays to $B_s^{(*)}\bar{B}_s^{(*)}$ pairs as well as to $B^{(*)}\bar{B}^{(*)}$ pairs and to final states with bottomonia, discussed later in this paper: the relative production fractions are denoted by $f_s$, $f_{ud}$ and $f_B$, respectively, and by definition they sum up to unity: $f_s + f_{ud} + f_B = 1$. The parameter $f_s$ is a key ingredient to calculate the total $B_s$ yield in the sample, $N(B_s) = 2 \cdot \mathcal{L} \cdot \sigma_{bb} \cdot f_s$, where $\mathcal{L}$ is the integrated luminosity of the data and $\sigma_{bb}$ is the cross section of the process $e^+e^- \to bb$. The untagged branching fraction measurements presented in this review require $N(B_s)$ as normalization and thus rely on $f_s$. Since the parameter $f_s$ plays such a central role for the normalization of the measurements, we discuss its determination in the following.
The principle of all $f_s$ measurements is to compare decay rates to a chosen final state measured in a $B_s$-enriched and a $B_s$-depleted sample. One measures for example the inclusive $D_s$ rates in data recorded at $\Upsilon(5S)$ ($B_s$ enriched) and $\Upsilon(4S)$ ($B_s$ depleted). Belle applied this method to the full 121.4 fb$^{-1}$ data sample collected at the $\Upsilon(5S)$ resonance and obtained the value $f_s = (17.2 \pm 3.0)\%$, corresponding to $(7 \pm 1)$ million $B_s^{(*)}\bar{B}_s^{(*)}$ pairs. The dominant uncertainty in this kind of $f_s$ measurement arises from the uncertainty on the prediction for the branching fraction $\mathcal{B}(B_s \rightarrow D_s X)$, which is taken from a model-dependent estimate.\[11\] There are variants of this $f_s$ measurement that use inclusive $D^0$, $\phi$ or $B$ yields.\[10\] The available published measurements were combined and result in $f_s = (19.9 \pm 3.0)\%$.\[3\]

An approach that avoids the dependence on hadronic branching fractions, which are difficult to predict, uses dilepton events where the leptons stem from semileptonic $B_s$ decays.\[15\] The inclusive semileptonic $B_s$ branching fraction can be estimated with relatively high precision from the well measured $B^0$ branching fraction, and the $B^0$ and $B_s$ lifetimes $\tau_s$ and $\tau_d$ assuming SU(3) flavor symmetry:

$$\mathcal{B}(B_s \rightarrow X \ell \nu) = \mathcal{B}(B^0 \rightarrow X \ell \nu) \cdot \frac{\tau_s}{\tau_d}. \quad (2)$$

The charge of the lepton ($\ell = e, \mu$) from the semileptonic decay is sensitive to the flavor of the decaying $b$-quark. Since the mixing probability for a $B_s$ meson, $\chi_s = (49.9309 \pm 0.0012)\%$, is much higher than for a $B^0$ meson, $\chi_d = (18.75 \pm 0.20)\%$, and
no mixing occurs for \( B^+ \) mesons, the measured rates of dilepton events with same-sign \( \ell^+\ell^\pm \) pairs (\( B_s \)-enhanced) and opposite-sign \( \ell^+\ell^\mp \) pairs (\( B_s \)-depleted) can be used to extract \( f_s \). So far, no results with this method have been published. The expected precision on \( f_s \) is 10 to 15\%, which would be equal to or better than the combination of all existing measurements.

Not only the fraction of events containing \( B_s^{(*)} \) mesons, but also the fractions of the different modes \( B_s \bar{B}_s, B_s^* \bar{B}_s \) and \( B_s^* \bar{B}_s \) are of interest. These can be obtained from a fit to the \( \Delta E-M_{bc} \) distribution of fully reconstructed \( B_s \to D_s^- \pi^+ \) decays (see Fig. 1).\[17\] The most common mode is \( B^*_s \bar{B}_s^* \) with a fraction of \( f_{B^*_s B^*_s} = (87.0 \pm 1.7)\%.\[18\]

### 2.2 \( CP \) violating decay modes

Decay time distributions of \( B_s \) decays to final states such as \( J/\psi \phi \) give access to the \( CP \) violating phase of \( B_s^0 \bar{B}_s^0 \) oscillations, \( \phi_s \), and the decay width difference \( \Delta \Gamma_s = \Gamma_L - \Gamma_H \) of the light and heavy \( B_s \) mass eigenstates. Measurements of such \( B_s \) decay time distributions are the domain of the LHCb experiment as it collects large \( B_s \) samples with high boosts of the \( B_s \) mesons, and has an excellent timing resolution sensitive to the fast \( B_s \)-oscillations. Measurements with \( \Upsilon(5S) \) data can contribute to a better understanding of the resonance structure in the decays and provide measurements of the absolute branching fractions. The measurements in this section are untagged and use the variables \( M_{bc} \) and \( \Delta E \) for signal extraction.

The \( J/\psi \phi \) final state is a superposition of \( CP \)-even and \( CP \)-odd states and therefore \( \phi_s \) and \( \Delta \Gamma_s \) have to be extracted in an angular analysis.\[19\] Precise knowledge of the underlying resonant and non-resonant backgrounds is vital in this procedure. Belle studied the contribution of \( \phi \to K^+K^- \), \( f'_2(1525) \to K^+K^- \) and the remaining non-resonant components to the total \( B \to J/\psi K^+K^- \) decay width by fitting the different contributions to the \( K^+K^- \) invariant mass distribution.\[20\] The underlying S-wave component in the \( \phi \) mass window is measured taking into account the possibility of an additional \( B_s \to J/\psi f_0(980) \) component. This approach provides complementary information to the time dependent angular analysis by LHCb.\[21\]

An angular analysis is not necessary to determine the \( CP \) violating parameters, if the \( B_s \) decays to a \( CP \) eigenstate, for example \( J/\psi f_0(980) \). The \( B \to J/\psi f_0(980) \) decay was observed in 2011 at the same time by LHCb and Belle.\[22\][23\) Belle also claimed evidence for the decay \( B \to J/\psi f_0(1370) \).\[23\] Moreover, Belle reported the first observation of the \( B_s \) decays to the \( CP \)-even states \( J/\psi \eta \), with \( \eta \to \gamma \gamma \) and \( \eta \to \pi^+\pi^-\pi^0 \) (see Fig. 2), and \( J/\psi \eta' \), with \( \eta' \to \eta \pi^+\pi^- \) and \( \eta' \to J/\psi \gamma \).\[24\] A further study was dedicated to the decays of \( B_s \) mesons to \( K^+K^- \) and \( K^0\bar{K}^0 \).[25]

The \( \Upsilon(5S) \) data sample also allowed for the measurement of the \( B_s \to D_s^{(*)}+D_s^{(*)} \) branching fractions.\[26\][27\) Such decay modes can be measured with less model dependence than at hadron colliders, due to the presence of two low-energy photons. The measurements put constraints on the parameter space of the decay width difference \( \Delta \Gamma_s \) and the angle \( \phi_{12} = \text{arg}(M_{12}/\Gamma_{12}) \), where \( M_{12} \) and \( \Gamma_{12} \) are the off-diagonal elements of the \( B_s \) mass and decay matrices. Under certain theory assumptions it can be deduced from this measurement that \( \phi_{12} \lesssim 40^\circ \).[28]
Figure 2: $M_{bc}$ and $\Delta E$ distribution of $B_s \to J/\psi\eta(\gamma\gamma)$ events reconstructed in 121.4 fb$^{-1}$ of $\Upsilon(5S)$ data collected with the Belle detector. The distributions show projections to the $B_s^*\bar{B}_s^*$ signal region of the other variable, $\Delta E \in (-116; 12)$ MeV and $M_{bc} \in (5.405; 5.428)$ GeV/c$^2$. The solid curves are the projections of the fit result, the dotted curves represent the background shape. Reprinted figure with permission from J. Li et al. [Belle Collaboration], Phys. Rev. Lett. 108, 181808, 2012. Copyright (2012) by the American Physical Society.

The measured branching fractions of the $CP$ violating $B_s$ decay modes are summarized in Table 1. It is worthwhile pointing out that the systematic uncertainties of all measurements are dominated by the $\sim 15\%$ uncertainty on $f_s$. Current methods of $f_s$ determination are statistically limited and substantial improvement of the precision can be expected with a larger $\Upsilon(5S)$ data sample at a next generation $B$-factory.

### 2.3 Semileptonic decays

Semileptonic decays of $B_{(s)}$ mesons are a powerful tool to determine the elements $|V_{cb}|$ and $|V_{ub}|$ of the CKM matrix, to probe the quark dynamics inside the $B_{(s)}$ meson and to study $CP$ violation. The inclusive branching fraction, $\mathcal{B}(B_s \to X\ell \nu)$, where $X$ is an arbitrary hadronic final state and $\ell = e, \mu$, is an important parameter in the determination of the $B_s$ production fraction at the $B$-factories and the LHC.[29] The SU(3) symmetry relation given by Eq. 2 is often used in these measurements to estimate the branching fraction $\mathcal{B}(B_s \to X\ell \nu)$. Theory calculations predict that this equality holds at the percent level,[30, 31] but this has to be proven in experimental tests. The $B\bar{B}AR$ collaboration measured the branching fraction $\mathcal{B}(B_s \to \ell\nu X) = (9.5^{+2.5}_{-2.0}(\text{stat})^{+1.1}_{-1.9}(\text{syst}))\%$ with 4.25 fb$^{-1}$ of data collected in the center-of-mass energy range between 10.54 GeV and 11.20 GeV.[32]

The Belle collaboration profited from their large $\Upsilon(5S)$ data sample to perform the most precise measurement of the $B_s \to X\ell\nu$ branching fraction.[33] This decay mode has a large event yield due to the large expected branching fraction ($\sim 10\%$ for each flavor, $e$ and $\mu$), and as only the charged lepton is reconstructed, it can be detected with high efficiency. Consequently, it was feasible to tag $B_s\bar{B}_s$ pair events by reconstruction of $D^+_s$ mesons from the Cabibbo-favored decay mode $\bar{B}_s \to D^+_s X$, which has a large probability of $(93 \pm 25)\%$.[3] The $D^+_s$ tag enhances the relative number of $B_s$ mesons in
the sample from 20% to approximately 70%. The tag $D_{s}^{+}$ mesons are reconstructed in the clean $D_{s}^{+} \rightarrow \phi(\rightarrow K^{+}K^{-})\pi^{+}$ decay mode. To ensure that the tag $D_{s}^{+}$ and the signal lepton $\ell$ stem from different $B_{s}$ mesons, they are required to have the same sign of the electric charge, as illustrated in Fig. 3 (left). The same-sign requirement implies that due to $B_{s}$ mixing, only $\chi_{s} \approx 50\%$ of the signal leptons are selected.

Two samples were analysed: one containing all $D_{s}^{+}$ candidates and the other all $D_{s}^{+}\ell^{+}$ candidates. The yield of correctly reconstructed $D_{s}^{+}$ mesons is obtained from fits to the $K^{+}K^{-}\pi^{+}$ invariant mass distributions. The $D_{s}^{+}\ell^{+}$ sample contains not only signal leptons, but also secondary leptons from decays of $B_{s}$ daughters and misidentified lepton candidates. The yield of signal leptons is obtained from a fit to the lepton momentum spectrum (see Fig. 3 (right)).

The $B_{s} \rightarrow X \ell\nu$ branching fraction is calculated from the efficiency-corrected $D_{s}^{+}$ and $D_{s}^{+}\ell^{+}$ yields. The yields include contributions from the $B^{0}$ and $B^{+}$ decays: $B \rightarrow D_{s}^{+} X$ and $B \rightarrow X \ell\nu$. The fraction of $B_{s}$ events in the $D_{s}^{+}$ and $D_{s}^{+}\ell^{+}$ samples is estimated from external measurements, including $f_{s}$ and the $B_{s}$ mixing probability. The external parameters and the resulting uncertainties are listed in Table 2. The extracted $B_{s} \rightarrow X \ell\nu$ branching fraction is $(10.6 \pm 0.5\,(\text{stat}) \pm 0.7\,(\text{syst}))\%$, in agreement with the theory predictions. [30, 31]

This analysis is a good example for the benefits of the coherent production of $B_{s}^{(s)}\bar{B}_{s}^{(s)}$ pairs at an $e^{+}e^{-}$ $B$ factory. Tagging one $B_{s}$ meson in the event with a reconstructed $D_{s}^{+}$ meson allows one not only to study semileptonic $B_{s}$ decays inclusively, it also reduces

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Table 1: Branching fraction measurements of $CP$ violating decay modes. All results are obtained using the full Belle $\Upsilon(5S)$ data sample (121.4 $fb^{-1}$). The statistical and systematic uncertainties of the branching fractions are added quadratically.

| $B_{s}$ decay mode | Branching fraction [10^{-3}] | Signal yield | Ref. |
|---------------------|-----------------------------|--------------|------|
| $J/\psi\eta$       | 0.51 ± 0.13                 | 141±14       | 24   |
| $J/\psi\eta'$      | 0.37 ± 0.10                 | 86±14        | 24   |
| $J/\psi f_{0}(980), f_{0}(980) \rightarrow \pi^{+}\pi^{-}$ | 0.12 ± 0.04 | 63±16 | 23   |
| $J/\psi f_{0}(1370), f_{0}(1370) \rightarrow \pi^{+}\pi^{-}$ | 0.034 ± 0.014 | 19±6 | 23   |
| $J/\psi\phi$       | 1.25 ± 0.24                 | 326±19       | 20   |
| $J/\psi f_{2}^{+}(1525)$ | 0.26 ± 0.08 | 60±13 | 20   |
| $J/\psi K^{+}K^{-}$ | 1.01 ± 0.22                 | 536±32       | 20   |
| $K^{+}K^{-}$        | 0.038 ± 0.012               | 23±6         | 25   |
| $K^{0}\bar{K}^{0}$ | < 0.066 at 90% C.L.          | 5±5          | 25   |
| $D_{s}^{+}D_{s}^{-}$ | 5.8 ± 1.7                  | 33±6         | 26   |
| $D_{s}^{*+}D_{s}^{*-}$ | 18 ± 5 | 45±6 | 26   |
| $D_{s}^{*+}D_{s}^{*-}$ | 20 ± 6 | 24±4 | 26   |
| $D_{s}^{(*)+}D_{s}^{(*)-}$ | 43 ± 11 | — | 20   |
Figure 3: Measurement of the $B_s \to X\ell\nu$ branching fraction: The diagram on the left illustrates how the selection of same-sign $D_s^+\ell^+$ combinations ensures that the signal lepton $\ell^+$ and the tag $D_s^+$ meson stem from different $B_s$ decays. The distribution on the right shows the measured electron momentum spectrum for events with correctly reconstructed tag $D_s^+$. Reprinted figure with permission from C. Oswald et al. [Belle Collaboration], Phys. Rev. D 87, 072008, 2013. Copyright (2013) by the American Physical Society.

the systematic uncertainty on the $B_s$ production fraction, which is $\sim 6\%$, compared to $\sim 15\%$ in the untagged measurements.

2.4 Hadronic decays

Studies of the hadronic decays $B_s \to D_s^{(*)}h$ with $h = \pi^+, K^\pm, \rho^+$ were amongst the earliest $B_s$ measurements performed with 23.6 fb$^{-1}$ of the Belle $\Upsilon(5S)$ data set and will not be discussed here.\footnote{17, 34} These measurements test theory calculations that predict similar branching fractions for $B_s$ and $B^0$ decays based on SU(3) symmetry.\footnote{35}

There have also been studies of baryonic $B_s$ decay modes. Baryonic decays of lighter $b$-flavored mesons, for example $B^+ \to \Lambda_c^- p \pi^+$, were discovered before, and an enhancement

Table 2: Parameters for the extraction of the $B_s \to X\ell\nu$ branching fraction and the resulting relative uncertainties.

| Parameter(s)                                      | Relative uncertainty on $B(B_s \to X\ell\nu)$ |
|--------------------------------------------------|-----------------------------------------------|
| $B_s$ production fraction: $f_s$                  | 2.4\%                                         |
| $B^0, B^+$ production fraction: $f_u, f_d$        | 1.0\%                                         |
| $B_s \to D_s^{\pm}X$ multiplicity                | 4.4\%                                         |
| $B \to D_s X$ branching fractions                 | 3.1\%                                         |
| $B \to X\ell\nu$ branching fractions              | 0.4\%                                         |
| $B^{(*)}\bar{B}^{(*)}(\pi)$ hadronization fractions | 0.3\%                                         |
| $B^0$ and $B_s$ mixing probabilities              | 0.2\%                                         |
of the branching fraction in the baryon-antibaryon mass spectrum near the kinematic threshold was observed.\cite{36, 37, 38} This aroused interest in studies of the corresponding $B_s$ decays. Recently, Belle found evidence for the decay $B_s \rightarrow \Lambda_c^- \Lambda \pi^+$ and measured the branching fraction $(3.6 \pm 1.1\text{(stat)} \pm 1.2\text{(syst)}) \times 10^{-4}$.\cite{39} Unfortunately, the $\Upsilon(5S)$ data sample is not large enough to make a statement on the phenomenon of a branching fraction enhancement near threshold as observed for $B$ decays.

2.5 Radiative penguin decays

Measurements of branching fractions and kinematic spectra of processes that are suppressed in the Standard Model (SM) are a promising indicator for “new physics” because the decay rate could be significantly enhanced by loop contributions involving particles beyond the SM. In $B_s$ decays, unique $b \rightarrow s$ flavor changing neutral current transitions can be studied, such as $B_s \rightarrow \phi \gamma$ and $B_s \rightarrow \gamma \gamma$. In the SM, these decays proceed via so-called penguin diagrams, whose branching fractions were predicted to be at the order of $4 \times 10^{-5}$ and $5 \times 10^{-7}$, respectively.\cite{40, 41} In the initial 23.6 fb$^{-1}$ data sample collected at $\Upsilon(5S)$, Belle observed the decay $B_s \rightarrow \phi \gamma$ for the first time and measured its branching fraction to be $(57^{+18}_{-15}\text{(stat)}^{+12}_{-11}\text{(syst)}) \times 10^{-6}$, consistent with the SM expectation, which was later confirmed by LHCb.\cite{42, 43} No significant signal was observed for the $B_s \rightarrow \gamma \gamma$ decay and the upper limit of $8.7 \times 10^{-6}$ on the branching fraction was set at the 90% confidence level.\cite{42}

3 Bottomonium Spectroscopy at $\Upsilon(5S)$

A data sample obtained from $e^+e^-$ collisions at the mass of the $\Upsilon(5S)$ would not have been selected a priori as a likely sample with which to pursue spectroscopy of narrow bottomonia. Both the $\Upsilon(4S)$ and $\Upsilon(5S)$, being above open-flavor threshold, dominantly decay to open bottom mesons: $B^{(*)}\bar{B}^{(*)}, B_s\bar{B}_s$. The partial widths of $\Upsilon(4S)$ and $\Upsilon(5S)$ to $\pi^+\pi^-\Upsilon(nS)$ (where $n = 1, 2, 3$) were expected to be similar to those for $\Upsilon(3S)$ to $\pi^+\pi^- (\Upsilon(2S), \Upsilon(1S))$ - which implies an expected branching fraction for such transitions that would be far too small for lower bottomonium states to be profitably studied through them. In studies both by BaBar\cite{47} and Belle\cite{48}, the partial widths for $\Upsilon(4S) \rightarrow \pi^+\pi^- (\Upsilon(2S), \Upsilon(1S))$ were measured and satisfied these expectations. However, the expectations were shown to be completely incorrect in the case of $\Upsilon(5S)$. In the following sections we describe both the measurement of these anomalously large $\Upsilon(5S) \rightarrow \pi^+\pi^- (\Upsilon(3S), \Upsilon(2S), \Upsilon(1S))$ transition rates in the Belle data as well as the subsequent discovery of several conventional and unconventional bottomonium states and transitions among them.
3.1 Observation of anomalously large $\pi^+\pi^-$ transition rates from $\Upsilon(5S)$ to lower bottomonia

Using a sample of 21.7 fb$^{-1}$ of $e^+e^-$ collisions at the $\Upsilon(5S)$, Belle observed very large rates for the transitions $\Upsilon(5S) \rightarrow \pi^+\pi^- \Upsilon(1S, 2S, 3S)$: up to 100 times larger than the corresponding rates for $\pi^+\pi^-$ transitions between $\Upsilon(nS)$ ($n = 1, 2, 3$) states that lay below the open-bottom threshold, or even from $\Upsilon(4S)$.[49] Immediately upon this observation, speculation ensued concerning the explanation of this wildly unexpected result. Several explanations were offered, including the existence of tetraquark or other exotic non-$\Upsilon(nS)$ states near $\Upsilon(5S)$.[50]
3.2 Spectroscopy of conventional bottomonium states

The currently-known bottomonium spectrum is shown in Fig. 4. The S-wave triplet states, Υ(nS), and the P-wave triplet states, χ_b(1P) and χ_b(2P), have been known for many years, while the ground state S-wave singlet, η_b(1S), was discovered in Υ(3S) → η_b(1S)γ decays only in 2008 by BABAR and confirmed by CLEO.[51, 52, 53] The bottomonium states recently discovered using the Υ(5S) data sample at Belle are the two lower-lying P-wave singlets, h_b(1P) and h_b(2P), and the second S-wave singlet, η_b(2S). The discoveries of these states are detailed in the following sections.

3.2.1 Discovery of singlet-P states h_b(mP)

The observation of large rates for π⁺π⁻ transitions of Υ(5S) to lower vector bottomonia made attractive the possibility of searching for transitions to other, previously unobserved states such as the singlet-P and excited singlet-S states. Additional motivation for these searches came from the CLEO observation of the production of the singlet-P charmonium state h_c via the process e⁺e⁻ → π⁺π⁻h_c at a center-of-mass energy of 4.16 GeV, lying above charm threshold.[54] The rate for this transition is comparable to that for e⁺e⁻ → π⁺π⁻J/ψ, which is surprising, since the transition to h_c requires a constituent charm quark to undergo a spin flip and should therefore be suppressed relative to the transitions between vector charmonia, which do not require a charm quark spin flip.

The search for h_b(mP) states (where m = 1, 2) was done using a hadronic event selection in which at least one oppositely-charged pair of positively-identified pions was observed. Only the information from the two charged pions was used, and the yield of h_b(mP) production was obtained from the spectrum of the π⁺π⁻ missing mass, which is defined as

\[ M_{\text{miss}} \equiv \sqrt{(P(\Upsilon(5S)) - P(\pi^+\pi^-))^2 = \sqrt{[M(\Upsilon(5S)) - E^*_{\pi^+\pi^-}]^2 - [p^*_{\pi^+\pi^-}]^2}}, \tag{3} \]

where energies and momenta are measured in the center-of-mass frame. The yields were determined using a binned maximum-likelihood fit to the π⁺π⁻ missing mass spectrum for all π⁺π⁻ pairs in selected events. The fit function utilizes a background function composed of a simple polynomial to account for the combinatorial π⁺π⁻ background, and a threshold function representing the onset of the inclusive K_S threshold at M_{miss} values of approximately M(Υ(5S)) - M(K_S). To account for the signal due to π⁺π⁻ transitions from Υ(5S), a reversed Crystal Ball function (a normal Crystal Ball function[55] with the tail on the high, rather than the low mass, side of the curve) was used. The shape parameters for the signal function were obtained from a data sample of fully reconstructed transitions Υ(5S) → π⁺π⁻Υ(nS) (n=1,2,3) with Υ(nS) → μ⁺μ⁻. This method not only provided a data-driven shape for the inclusive π⁺π⁻ signal, but also provided a check on the mass scale obtained using the π⁺π⁻ missing mass.

In the fit, signals corresponding to π⁺π⁻ transitions to all three Υ(nS), the two lower h_b(mP) states and Υ(1D) were used, as well as functions corresponding to transitions Υ(3S) → π⁺π⁻Υ(1S) and Υ(2S) → π⁺π⁻Υ(1S) in which the Υ(3S) and Υ(2S) were
Figure 5: The spectrum of missing mass, $M_{\text{miss}}$, used by the Belle Collaboration to search for $\Upsilon(5S) \rightarrow \pi^+\pi^-h_b(\text{mP})$ decays, shown after background subtraction. The functional form of the fitted curve is described in the text. The peaks in the spectrum arise from direct transitions $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S,3S)$, $\Upsilon(5S) \rightarrow \pi^+\pi^-h_b(\text{mP})$ and $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1D)$. There are also peaks which are displaced from their expected location at $M(\Upsilon(1S)) = 9.46\text{GeV}/c^2$ due to cascade transitions $\Upsilon(5S) \rightarrow X + \Upsilon(3S,2S)$; $\Upsilon(3S,2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, wherein we observe only the lower transition $\pi^+\pi^-$ pair. These peaks are labelled $\Upsilon(3S) \rightarrow \Upsilon(1S)$ and $\Upsilon(2S) \rightarrow \Upsilon(1S)$ in the spectrum. Reprinted figure with permission from I. Adachi et al. [Belle Collaboration], Phys. Rev. Lett. 108, 032001, 2012. Copyright (2012) by the American Physical Society.

produced inclusively in unobserved transitions from $\Upsilon(5S)$. The final $\pi^+\pi^-$ missing mass spectrum is shown in Fig. 5 with the fitted background subtracted, and with the fitted signal functions overlaid. The significances of the $h_b(1P)$ and $h_b(2P)$ signals, with systematic uncertainties accounted for, are 5.5$\sigma$ and 11.2$\sigma$, respectively. These measurements represent the first observation of the singlet-$P$ states of bottomonium. Previously, there was only weak evidence for $h_b(1P)$ presented by BABAR, who sought it in the transition $\Upsilon(3S) \rightarrow \pi^0h_b(1P) \rightarrow \pi^0\gamma h_b(1S)$.

One important item to note is that, while the $h_b(\text{mP})$ search was prompted in part by the observation of anomalously large rates for $\pi^+\pi^-$ transitions from $\Upsilon(5S)$, the rates for production of $h_b(\text{mP})$ obtained by this analysis are also unexpectedly high. The ratios $R \equiv \frac{\sigma(\Upsilon(5S) \rightarrow h_b(\text{mP})\pi^+\pi^-)}{\sigma(\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-)}$ were determined to be $R = 0.45 \pm 0.08(\text{stat})^{+0.07}_{-0.12}(\text{syst})$ for the $h_b(1P)$ and $R = 0.77 \pm 0.08(\text{stat})^{+0.22}_{-0.17}(\text{syst})$ for the $h_b(2P)$. Hence the same non-suppression of the spin flip transition from $\Upsilon(5S)$ to $h_b(\text{mP})$ is observed as was observed in the charmonium case reported by CLEO.

The investigation of the reasons for this non-suppression ultimately led to the discovery of the charged $Z_b$ states, which will be described later in Sec. 3.3.1. Nearly all the $\pi^+\pi^-$ transitions to the $h_b(\text{mP})$ states occur through the $Z_b$ as an intermediate state, and this observation enabled a substantial decrease in the combinatorial background (by a factor
3.2.2 Observation of radiative transitions \( h_b(mP) \rightarrow \gamma \eta_b(m^S) \)

Subsequent to the observation of the singlet-P states, Belle launched a study of the expected principal decay modes of the singlet-P states, namely, the E1 transitions \( h_b(1P) \rightarrow \gamma \eta_b(1S) \), \( h_b(2P) \rightarrow \gamma \eta_b(1S) \), and \( h_b(2P) \rightarrow \gamma \eta_b(2S) \).\[57\] The branching fractions for these three transitions were predicted by Godfrey and Rosner to be 41.4%, 12.5% and 19.3%, respectively.\[58\] The search involved selection of events broadly consistent with the production via \( \pi^+\pi^- \) transition of either \( h_b(mP) \) state, consistent with the intermediate production of a \( Z_b \) state, and the observation of a photon. A two-dimensional method was then employed, in which the \( h_b(mP) \) yield was determined in bins of the variable \( M_{\text{miss}}^{(m)}(\pi^+\pi^-) = M_{\text{miss}}(\pi^+\pi^-) - M_{\text{miss}}(\pi^+\pi^-) + M(h_b(mP)) \). The \( \eta_b(m^S) \) yield was obtained by binned maximum-likelihood fits to the variable \( M_{\text{miss}}^{(m)}(\pi^+\pi^-\gamma) \). The distributions of this variable for events corresponding to each transition are shown in Fig.[3]

These investigations yielded the first observation of the radial excitation of \( \eta_b(1S) \), namely \( \eta_b(2S) \), with \( M(\eta_b(2S)) = (9999.0 \pm 3.5 \text{(stat)} \pm 4.2 \text{(syst)}) \text{ MeV}/c^2 \), and measurements of the branching fractions for \( h_b(mP) \rightarrow \gamma \eta_b(m^S) \) (\( m' = 1, 2 \)) (see Table[3]). The resulting hyperfine splitting in the 2S level, of \( \Delta M_{\text{HF}}(2S) = 24.3^{+4.0}_{-4.8} \text{MeV}/c^2 \), was found to be in agreement with theoretical expectations.\[59\]\[60\] while the branching fractions were, in general, larger than the predicted values.\[58\] A 90% confidence level upper limit for the width of \( \eta_b(2S) \) was set at 24 MeV/c^2. In addition, the combined samples of events in which the \( \eta_b(1S) \) was observed enabled Belle to make the world’s most precise measurement of the \( \eta_b(1S) \) mass, \( M(\eta_b(1S)) = (9402.4 \pm 1.5 \text{(stat)} \pm 1.8 \text{(syst)}) \text{ MeV}/c^2 \), and to measure its width for the first time: \( \Gamma(\eta_b(1S)) = 11^{+8}_{-6} \text{ MeV}/c^2 \). The 1S hyperfine splitting of \( \Delta M_{\text{HF}}(1S) = 57.9 \pm 2.3 \text{ MeV}/c^2 \) that corresponds to the \( \eta_b(1S) \) mass measurement is in much better agreement with theoretical expectations than are previous measurements.\[59\]\[60\]
Figure 6: The spectrum of the variable $M_{\text{miss}}^{(m)}(\pi^+\pi^-\gamma)$, used by Belle to search for $h_b(mP) \to \gamma\eta_b(m'S)$ decays. A fit was performed to these data, where the signal was modelled as a Crystal Ball line shape convoluted with a Breit-Wigner function, and the background was modelled as exponential polynomial. The peaks in the spectrum arise from $h_b(1P) \to \gamma\eta_b(1S)$ (left), $h_b(2P) \to \gamma\eta_b(1S)$ (middle) and $h_b(2P) \to \gamma\eta_b(2S)$ (right). Figure courtesy of the Belle Collaboration.

3.2.3 Observation of $\pi^+\pi^-$ transitions to $D$-wave states

Among the peaks observed in the $\pi^+\pi^-$ missing mass distribution for the inclusive $\Upsilon(5S) \to \pi^+\pi^- + X$ analysis is a peak that corresponds to $\pi^+\pi^-$ transitions to the $\Upsilon(1D)$ states at 10.16 GeV. In the inclusive analysis, the significance of the peak was insufficient (at only 2.6$\sigma$) to claim observation. Belle undertook a fully exclusive analysis in order to establish observation of the $\Upsilon(1D)$ state, reconstructing the full decay chain $\Upsilon(5S) \to \pi^+\pi^- \Upsilon(1D); \Upsilon(1D) \to \gamma\chi_{bJ}(1P); \chi_{bJ}(1P) \to \gamma\Upsilon(1S); \Upsilon(1S) \to \mu^+\mu^-$, and establishing a signal for $\Upsilon(5S) \to \pi^+\pi^- \Upsilon(1D)$ at the 9$\sigma$ level of significance. Interestingly, the observed yield indicates a partial width for the $\Upsilon(5S) \to \pi^+\pi^- \Upsilon(1D)$ of $\sim 60$ keV/$c^2$, which is much larger than expected.

3.2.4 Observation of $\eta$ transitions to $\Upsilon(1S, 2S)$

Transitions between vector meson states via the emission of an $\eta$ meson are of interest historically in part because of the observation of a larger than expected branching fraction for $\psi(2S) \to \eta J/\psi$, (3.3 $\pm$ 0.5)$\%$, compared to that for $\psi(2S) \to \pi^+\pi^- J/\psi$, (34.0 $\pm$ 0.4)$\%$. The QCD multipole expansion model allows one to classify hadronic transitions between heavy quarkonium states as arising from the emission and subsequent hadronization of a pair of gluons that are emitted in various combinations of chromo-electric or chromo-magnetic multipoles. The simplest such transitions, $\pi^+\pi^-$ transitions, occur due to the emission of, in lowest order, a pair of chromo-electric dipole (E1) gluons. $\eta$ transitions require a higher order combination, an E1 gluon and a chromo-magnetic quadrupole (M2) gluon. Hence, in the transition between any two vector states, the rate for the $\eta$ transition ought to be substantially suppressed relative to that for the $\pi^+\pi^-$ transition between the same states.
A recent Belle observation of the transition $\Upsilon(2S) \rightarrow \eta \Upsilon(1S)$ was consistent with the expectation of suppression, in which the ratio of rates for $\eta$ to that for the corresponding $\pi^+\pi^-$ transition of $(1.99 \pm 0.14 \text{ (stat)} \pm 0.08 \text{ (syst)}) \times 10^{-3}$ was measured. B\-A\-R, however, observed an unexpectedly high rate for the $\Upsilon(4S) \rightarrow \eta \Upsilon(1S)$ transition, measuring a $\eta$ to $\pi^+\pi^-$ rate ratio of $2.41 \pm 0.40 \text{ (stat)} \pm 0.21 \text{ (syst)}$. This result indicated a possible breakdown of the QCD multipole expansion model for transitions from states lying above open-flavor threshold, and motivated a search for $\eta$ transitions from the $\Upsilon(5S)$ by Belle.

The Belle analysis of the transitions $\Upsilon(5S) \rightarrow \eta(\Upsilon(1S), \Upsilon(2S))$ involved full reconstruction of the entire decay chain, with $\eta \rightarrow \gamma\gamma$ and $(\Upsilon(1S), \Upsilon(2S)) \rightarrow \mu^+\mu^-$. Again, the ratio of rates for the $\eta$ transition was measured relative to that for the corresponding $\pi^+\pi^-$ transitions, and it was found that the $\eta$ transitions from $\Upsilon(5S)$ are also not substantially suppressed relative to the $\pi^+\pi^-$ transitions. Ratios of $0.16 \pm 0.04 \text{ (stat)} \pm 0.02 \text{ (syst)}$ and $0.48 \pm 0.05 \text{ (stat)} \pm 0.09 \text{ (syst)}$ for the transitions to $\Upsilon(1S)$ and to $\Upsilon(2S)$, respectively, were measured. Attempts to explain the lack of suppression of these $\eta$ transitions incorporate the possibility of either a tetraquark resonant substructure in the parent wave function, or rescattering through $BB$ pairs.

### 3.3 Spectroscopy of unconventional bottomonium states

Quantum Chromodynamics does not limit hadronic structures to configurations involving three quarks (baryons) and those involving a quark and an antiquark (mesons). It has in fact been something of a surprise that clear examples of tetraquarks ($qq\bar{q}\bar{q}$), pentaquarks ($qqqq\bar{q}$) or meson molecules ($q\bar{q})(q'\bar{q}')$ have not been unambiguously identified. One of the most important results of the study of the Belle $\Upsilon(5S)$ data sample is the discovery of a number of interesting states which are unambiguous examples of such unconventional structures.

#### 3.3.1 $Z_{b}^\pm(10610)$ and $Z_{b}^\pm(10650)$

If the dipion transitions from $\Upsilon(5S)$ to lower bottomonium states, both $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(5S) \rightarrow \pi^+\pi^- h_b(mP)$ proceeded by the emission of two gluons from the initial $bb$ state, then the production of vector $\Upsilon(nS)$ states would dominate, since the transition to $h_b(mP)$ requires a $b$-quark spin flip and is expected to be heavily suppressed. This is not what was observed, however – the ratios of partial widths for $\pi^+\pi^- h_b(mP)$ to those of $\pi^+\pi^-\Upsilon(nS)$ are of order one. If instead of being directly produced in the transition from $\Upsilon(5S)$, the $\pi^\pm$ were sequentially produced in a cascade of decays, the expected suppression of $h_b(mP)$ production would not necessarily occur. It is this fact that led to search for an explanation in the resonant substructure of the $\Upsilon(nS)\pi^+\pi^-$ and $h_b(mP)\pi^+\pi^-$ final states.

A study of the invariant mass of $\pi^\pm\Upsilon(nS)$ and $\pi^\pm h_b(1P)$ revealed resonances having masses between $\Upsilon(4S)$ and $\Upsilon(5S)$. Signals of each of these states, which are electrically charged, were clearly observed in each of five different decay channels, $\Upsilon(nS)\pi^\pm$ ($n = 1, 2, 3$) and $h_b(mP)\pi^\pm$ ($m = 1, 2$). These resonances are denoted $Z_{b}^\pm(10610)$ and $Z_{b}^\pm(10650)$.
Figure 7: The $M_{\text{miss}}(\pi)$ spectra for events consistent with the decay chain $\Upsilon(5S) \rightarrow \pi^+\pi^-h_b(1P)$ (left) and $\Upsilon(5S) \rightarrow \pi^+\pi^-h_b(2P)$ (right). These missing masses are equivalent to the invariant mass of $h_b(1P)\pi$ and $h_b(2P)\pi$, respectively. Reprinted figure with permission from A. Bondar et al. [Belle Collaboration], Phys. Rev. Lett. 108, 122001, 2012. Copyright (2012) by the American Physical Society.

$Z_b^\pm(10650)$. In Figure 7, are shown the single-pion missing masses $M_{\text{miss}}(\pi)$ for events consistent with $\pi^+\pi^-\text{transitions to } h_b(1P)$ and $h_b(2P)$.

Because of their large masses, these states necessarily have a bottom quark and antiquark as constituents – but because they are charged, they must also include another pair of quarks, and therefore they are unambiguously unconventional in their quark structure. Whether they are simply a tetraquark state, e.g. $|Z_b^\pm\rangle \equiv |b\bar{b}u\bar{d}\rangle$, or a molecular state remains to be seen. One interesting point worth considering is the relative proximity of their masses to the $BB^*$ and $B^*B^*$ thresholds, which lends credence to the possibility that they are molecular states containing a $B^{(*)}B^*$ pair. Such a description predicts equal total widths (as observed) and large branching fractions to the appropriate $B^{(*)}\bar{B}^*$ final state (also as observed, as discussed below). The properties of these states are summarized in Table 4. Both have isospin $I = 1$, positive G-parity, and are determined to have spin-parity $J^P = 1^+$ by angular analysis of their production and decay kinematics.

In an attempt to further elucidate the nature of these states, Belle investigated the resonant substructure of three-body final states of $[B^{(*)}B^{(*)}]^{\pm}\pi^\mp$. In this analysis, one of the daughter $B^{(*)}$ mesons was fully reconstructed, while the other was inferred using the missing mass of the reconstructed $B^{(*)}\pi$ system. It was observed that the $Z_b^0(10610)$ decays with a branching fraction of $(86.0 \pm 3.6)$% to $BB^*$, and that the $Z_b^\pm(10650)$ decays with a branching fraction of $(73.4 \pm 7.0)$% to $B^*\bar{B}^*$. These branching fractions are calculated under the assumption that the $Z_b^\pm$ decays solely to $B^{(*)}B^*$,
Table 4: Properties of multiquark bottomonium-like states.

| State           | Mass (MeV/c^2) | Width (MeV/c^2) | Reference |
|-----------------|----------------|-----------------|-----------|
| \(Z_b^+(10610)\) | 10607.2 ± 2.0  | 18.4 ± 2.4      | [67]      |
| \(Z_b^+(10650)\) | 10652.2 ± 1.5  | 11.5 ± 2.2      | [67]      |
| \(Z_b^0(10610)\) | 10609 ± 4 ± 4  | –               | [69]      |

\(\pi^\pm \Upsilon(nS)\) and \(\pi^\pm h_b(mP)\). This result does not represent definitive proof of the molecular nature of the \(Z_b\) states, but is strong evidence in its favor.

### 3.3.2 \(Z_b^0(10610)\)

Naturally, once Belle had identified charged \(Z_b\) states, one might additionally expect the existence of neutral isospin partners. In order to search for them, the analogous \(\pi^0\pi^0\) transitions \(\Upsilon(5S) \rightarrow \pi^0\pi^0\Upsilon(nS)\) were investigated and the final-state Dalitz plot was treated in a manner similar to that in the previously-described charged dipion study. The \(Z_b^0(10610)\) state was observed in the single \(\pi^0\) missing mass with a significance at the 6.5\(\sigma\) level, performing a combined fit to the \(\Upsilon(2S)\pi^0\pi^0\) and \(\Upsilon(3S)\pi^0\pi^0\) samples.[69] The measured mass of the state, \((10609 ± 4(stat) ± 4(syst))\) MeV/c\(^2\), suggests that it is the isospin partner of the charged \(Z_b^+(10610)\). In addition, there is slight evidence for an isospin partner for the higher mass charged \(Z_b\), but the statistical significance of about \(2\sigma\) is insufficient to claim observation.

### 3.3.3 \(Y_b(10890)\)

In 2008, as noted above in Sec. 3.1, Belle observed rates for transitions \(\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S)\) that were much larger than theoretical expectations.[49] To investigate this anomaly, the \(\pi^+\pi^-\Upsilon(1S, 2S)\) cross section was measured for center-of-mass energies in the range between 10.83 GeV and 11.02 GeV to search for potential states in addition to the conventional \(\Upsilon(5S)\). A peak was found in the cross section \(\sigma(e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-)\) \((n = 1, 2, 3)\) at \((10888^{+2.7}_{-2.0}(stat) ± 1.2(syst))\) MeV/c\(^2\) with a width of \((30.7^{+8.3}_{-7.6}(stat) ± 3.1(syst))\) MeV/c\(^2\).[70] The peak values and widths observed for transitions to each of the three lower \(\Upsilon(nS)\) states were mutually consistent. The fact that this value is displaced from the peak in the \(b\bar{b}\) cross section,[71] led to the inference of a possible exotic state \(Y_b\) that is nearly degenerate with \(\Upsilon(5S)\).[72] [73]

### 4 Outlook

The large \(\Upsilon(5S)\) data sample collected by the Belle experiment made possible numerous measurements of \(B_s\) decays and provided the unexpected possibility to study conventional and exotic bottomonium states. Many of these decays and bottomonium states were observed for the first time. Their observation calls for further high precision studies.
and brings up new questions, that require a considerably larger sample of Υ(5S) data. Such a sample will be collected by Belle II at SuperKEKB, the upgrade to the Belle detector. The accelerator and the detector will be online from 2015. The target instantaneous luminosity will be $8 \times 10^{35} \text{ cm}^{-2}/\text{s}^{-1}$, 40 times that of KEKB. Assuming the same data collection ratio of $\Upsilon(5S)/\Upsilon(4S)$ as that at Belle, we can anticipate an $\Upsilon(5S)$ sample of as much as 5 ab$^{-1}$ of data.

A 5 ab$^{-1}$ $\Upsilon(5S)$ sample contains approximately 300 million $B_s\bar{B}_s$ pairs and will allow for comprehensive studies of the decay rates of the $B_s$ with a completeness and accuracy comparable to that currently available for $B^0$ and $B^\pm$ mesons, thereby improving our understanding of $B$ physics. Comparative studies of $B^0$ and $B_s$ mesons will help to reduce the theoretical uncertainties related to quantities sensitive to new physics. Moreover, $B_s$ physics provides additional opportunities to probe new physics effects in $b \to s$ transitions. The most notable improvement for $B_s$ measurements is the possibility to exploit tagging techniques that have been so successfully applied at $\Upsilon(4S)$, allowing for high purity measurements of decays with neutrals and missing energy, and the reduction of uncertainties due to $f_s$ to only a few percent. The golden new physics search modes of Belle II will be the flavor-changing neutral-current transitions suppressed in the SM: $B_s \to \tau\tau$ ($\mathcal{B} = 8.9 \times 10^{-7}$)\,[74,75], $B_s \to \nu\bar{\nu}$ ($\mathcal{B} = 7.5 \times 10^{-8}$)\,[76,77] and $B_s \to \gamma\gamma$ ($\mathcal{B} = (0.7^{+2.5}_{-0.1}) \times 10^{-6}$)\,[41,77], which complement the high profile searches of $B_s \to \mu\mu$ at the LHC. Various outstanding problems in semileptonic $B$ decays can be well complemented by precise measurements in $B_s$ decays, where the heavier strange spectator quark leads to smaller theoretical uncertainties\.[78] Precise absolute branching fractions of Cabibbo-favored transitions, e.g. $B_s \to D_s^{(*)}h$, will test predictions of QCD in $B_s$ decays and SU(3) symmetry\.[72] With minimal trigger bias, Belle II can perform complete surveys of the full range of $B_s$ decay modes to complement programs at hadron machines. Despite the $B_s$ having an oscillation frequency too fast for measurements of time-dependent CP violation at Belle II, the experiment can still provide unique information on the weak mixing amplitude in $B_s$ decays with neutral final states, as well as studies of time independent CP violation.

Belle II will also play a leading role in the study of bottomonium and other hadron physics at the $\Upsilon(5S)$. These studies are highly sensitive to physics triggers, and hence are very challenging to perform at hadron colliders. With numerous discoveries and many unsolved puzzles, spectroscopy will move from an era of first observations to precision measurements, to clarify quantum numbers and states. The charged $Z_b^\pm$ states and the neutral $Z_b^0(10610)$, discovered by Belle, represent candidates for $B$-meson molecules. Whether these are bound states should be determined by proving the existence of a second neutral state, $Z_b^0(10650)$, and studies of radiative transitions, $Z_b \to B^{(*)}\bar{B}\gamma$.\,[80] There is also interest in the search for possible sibling states, $W_{b\bar{b}}^{(*)}$ ($J = 0, 1, 2$), decaying to $\chi_b$ or $\eta_b$, and light hadrons.\,[81] Future studies based on the missing mass method will profit from the considerably larger data sample. The $\Upsilon_b(10890)$, a candidate for a tetraquark state, attracted strong interest in the theory community. The measurement of $B^{(*)}\bar{B}^{(*)}$ and $B_s^{(*)}\bar{B}_s^{(*)}$ production rates at the $\Upsilon(5S)$ energy inconsistent with expectations from SU(3) symmetry is another hint for the existence of this exotic state and
needs further investigation. There are also candidates for tetraquark and molecule states in the charm sector, but currently no theory provides a consistent picture of the whole spectrum. The large $\Upsilon(5S)$ sample that will become available at Belle II will help to clarify the issues currently under discussion and will allow for many other physics studies, uniquely feasible at an $e^+e^-$ collider.

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### References

[1] D. Besson et al. [CLEO Collaboration], *Phys. Rev. Lett.* **54**, 381 (1985).

[2] D. M. J. Lovelock et al., *Phys. Rev. Lett.* **54**, 377 (1985).

[3] J. Beringer et al. [Particle Data Group Collaboration], *Phys. Rev. D* **86**, 010001 (2012) and 2013 partial update for the 2014 edition.

[4] M. Artuso et al. [CLEO Collaboration], *Phys. Rev. Lett.* **95**, 261801 (2005).

[5] G. Bonvicini et al. [CLEO Collaboration], *Phys. Rev. Lett.* **96**, 022002 (2006)

[6] N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).

[7] M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[8] R. Aaij et al. [LHCb Collaboration], *JHEP* **1308**, 117 (2013).

[9] The estimation of the $B_s$ production at the $\Upsilon(5S)$ resonance is described below.

[10] A. Drutskoy et al. [Belle Collaboration], *Phys. Rev. Lett.* **98**, 052001 (2007).

[11] Y. Amhis et al. [Heavy Flavor Averaging Group Collaboration], arXiv:1207.1158 [hep-ex].

[12] M. Suzuki, *Phys. Rev. D* **31**, 1158 (1984).

[13] G. Huang et al. [CLEO Collaboration], *Phys. Rev. D* **75**, 012002 (2007).

[14] A. Drutskoy et al. [Belle Collaboration], *Phys. Rev. D* **81**, 112003 (2010).

[15] R. Sia and S. Stone, *Phys. Rev. D* **74**, 031501 (2006). Erratum-ibid. **80**, 039901 (2009).
[16] R. Louvot, Ph.D. thesis No. 5213, École polytechnique fédérale de Lausanne (2012). [http://dx.doi.org/10.5075/epfl-thesis-5213]

[17] R. Louvot et al. [Belle Collaboration], Phys. Rev. Lett. 102, 021801 (2009).

[18] This result is obtained by the Belle collaboration using a similar method as described in Ref. [17] and the full Belle Υ(5S) data set (121.4 fb⁻¹).

[19] R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 87 112010 (2013).

[20] F. Thorne, et al. [Belle Collaboration], arXiv:1309.0704 [hep-ex].

[21] R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 87, 072004 (2013).

[22] R. Aaij et al. [LHCb Collaboration], Phys. Lett. B 698, 115 (2011).

[23] J. Li et al. [Belle Collaboration], Phys. Rev. Lett. 106, 121802 (2011).

[24] J. Li et al. [Belle Collaboration], Phys. Rev. Lett. 108, 181808 (2012).

[25] C. -C. Peng et al. [Belle Collaboration], Phys. Rev. D 82 072007 (2010).

[26] S. Esen et al. [Belle Collaboration], Phys. Rev. D 87 031101(R) (2013).

[27] S. Esen, et al. [Belle Collaboration], Phys. Rev. Lett. 105, 201802 (2010).

[28] C.-K. Chua, W.-S. Hou and C.-H. Shen, Phys. Rev. D 84, 074037 (2011).

[29] R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 85, 032008 (2012).

[30] I. I. Bigi, T. Mannel and N. Uraltsev, JHEP 1109, 012 (2011).

[31] M. Gronau and J. L. Rosner, Phys. Rev. D 83, 034025 (2011).

[32] J. P. Lees et al. [BABARCollaboration], Phys. Rev. D 85, 011101 (2012).

[33] C. Oswald et al. [Belle Collaboration], Phys. Rev. D 87, 072008 (2013).

[34] R. Louvot et al. [Belle Collaboration], Phys. Rev. Lett. 104, 231801 (2010).

[35] A. Deandrea, N. Di Bartolomeo, R. Gatto, G. Nardulli, Phys. Lett. B 318, 549 (1993).

[36] S. A. Dytman et al. [CLEO Collaboration], Phys. Rev. D 66, 091101 (2002).

[37] N. Gabyshev et al. [Belle Collaboration], Phys. Rev. Lett. 97, 242001 (2006).

[38] B. Aubert et al. [BABARCollaboration], Phys. Rev. D 78, 112003 (2008).

[39] E. Solovieva et al. [Belle Collaboration], Phys. Lett. B 726, 206 (2013).

[40] A. Ali, B. D. Pecjak and C. Greub, Eur. Phys. J. C 55, 577 (2008).
[41] L. Reina, G. Ricciardi and A. Soni, \textit{Phys. Rev. D} \textbf{56}, 5805 (1997).
[42] J. Wicht \textit{et al.} [Belle Collaboration], \textit{Phys. Rev. Lett.} \textbf{100}, 121801 (2008).
[43] R. Aaij \textit{et al.} [LHCb Collaboration], \textit{Phys. Rev. D} \textbf{85}, 112013 (2012).
[44] Gottfried K. \textit{Phys. Rev. Lett.} 40:598 (1978).
[45] Voloshin MB. \textit{Nucl. Phys.} B 154:365 (1979).
[46] Yan TM. \textit{Phys. Rev. D} 22:1652 (1980).
[47] B. Aubert \textit{et al.} [BaBar Collaboration], \textit{Phys. Rev. D} \textbf{78}, 112002 (2008).
[48] A. Sokolov \textit{et al.} [Belle Collaboration], \textit{Phys. Rev. D} \textbf{79}, 051103 (2009).
[49] K. F. Chen \textit{et al.} [Belle Collaboration], \textit{Phys. Rev. Lett.} \textbf{100}, 112001 (2008).
[50] Ali A, Hambrock C, Aslam MJ, \textit{Phys. Rev. Lett.} \textbf{104}, 162001 (2010).
[51] B. Aubert \textit{et al.} [BaBar Collaboration], \textit{Phys. Rev. Lett.} \textbf{101}, 071801 (2008).
[52] B. Aubert \textit{et al.} [BaBar Collaboration], \textit{Phys. Rev. Lett.} \textbf{102}, 29901 (2009).
[53] G. Bonvicini \textit{et al.} [CLEO Collaboration], \textit{Phys. Rev. D} \textbf{81}, 031104 (2010).
[54] T. K. Pedlar \textit{et al.} [CLEO Collaboration], \textit{Phys. Rev. Lett.} \textbf{107}, 041803 (2011).
[55] J. E. Gaiser, Ph.D. thesis, Stanford University, SLAC-255 (1982).
[56] Lees JP \textit{et al.} [BaBar Collaboration], \textit{Phys. Rev. D} \textbf{84}, 091101(R) (2011).
[57] R. Mizuk \textit{et al.} [Belle Collaboration], \textit{Phys. Rev. Lett.} \textbf{109}, 232002 (2012).
[58] S. Godfrey and J. L. Rosner, \textit{Phys. Rev. D} \textbf{66}, 014012 (2002).
[59] S. Meinel, \textit{Phys. Rev. D} \textbf{82}, 114502 (2010).
[60] R. J. Dowdall et al. [HPQCD Collaboration], \textit{Phys. Rev. D} \textbf{85}, 054509 (2012).
[61] I. Adachi \textit{et al.} [Belle Collaboration], \textit{Phys. Rev. Lett.} \textbf{108}, 032001 (2012).
[62] R. Mizuk, \texttt{arXiv:1303.0096}.
[63] Y. -P. Kuang, \textit{Front. Phys. China} \textbf{1}, 19 (2006).
[64] M. B. Voloshin, \textit{Prog. Part. Nucl. Phys.} \textbf{61}, 455 (2008).
[65] U. Tamponi \textit{et al.} [Belle Collaboration], \textit{Phys. Rev. D} \textbf{87}, 011104 (2013).
[66] M. B. Voloshin, \textit{Mod. Phys. Lett.} A 26, 773 (2011).
[67] A. Bondar et al. [Belle Collaboration], Phys. Rev. Lett. 108, 122001 (2012).
[68] I. Adachi et al. [Belle Collaboration], arXiv:1209.6450, presented at ICHEP2012.
[69] P. Krokovny et al. [Belle Collaboration], Phys. Rev. D 88, 052016 (2013).
[70] K. -F. Chen et al. [Belle Collaboration], Phys. Rev. D 82, 091106 (2010).
[71] B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 102, 012001 (2009).
[72] J. F. Liu and G. J. Ding, Eur. Phys. J. C 72, 1981 (2012).
[73] A. Ali, C. Hambrock and W. Wang, arXiv:1306.4470.
[74] C. Bobeth and U. Haisch, Acta Phys. Polon. B 44, 127 (2013).
[75] A. Dighe and D. Ghosh, Phys. Rev. D 86, 054023 (2012).
[76] A. Badin and A. APetrov, Phys. Rev. D 82, 034005 (2010).
[77] A. Gemintern, S. Bar-Shalom and G. Eilam, Phys. Rev. D 70, 035008 (2004).
[78] P. Urquijo, arXiv:1305.1234 [hep-ex].
[79] R. Fleischer, N. Serra and N. Tuning, Phys. Rev. D 83, 014017 (2011).
[80] A. G. Drutskoy, F. -K. Guo, F. J. Llanes-Estrada, A. V. Nefediev and J. M. Torres-Rincon, Eur. Phys. J. A 49, 7 (2013).
[81] A. E. Bondar, A. Garmash, A. I. Milstein, R. Mizuk and M. B. Voloshin, Phys. Rev. D 84, 054010 (2011).
[82] C. Hambrock, arXiv:1306.0695 [hep-ph].