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$\Upsilon(5S)$ Results at Belle[1]

Remi Louvot
(on behalf of the Belle collaboration)
Laboratoire de Physique des Hautes Énergies,
École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
E-mail: remi.louvot@epfl.ch

Abstract. The data sample recorded with the Belle detector at the KEKB B factory (Tsukuba, Japan) operating at the $\Upsilon(5S)$ energy provides interesting and new results about the B_s^0 mesons and the $\Upsilon(5S)$ resonance. Recent analyses, based on data samples collected at the $\Upsilon(5S)$ resonance (23.6 fb^{-1}) or near it (7.9 fb^{-1}), are presented with a special focus on the final results on the $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to D_s^{\mp} K^{\pm}$ decays, and on the intriguing $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ measurements.

The Belle experiment [1], located at the interaction point of the KEKB asymmetric-energy e^+e^- collider [2], was designed for the study of B mesons created by e^+e^- annihilation produced at a center-of-mass (CM) energy corresponding to the mass of the $\Upsilon(4S)$ resonance ($\sqrt{s} \approx 10.58$ GeV). After having recorded an unequaled sample of ~ 800 millions of $B\bar{B}$ pairs[2], the Belle collaboration started to record collisions at higher energies, opening the possibility to study other particles, like the poorly-known B_s^0 meson. Up to now, 23.6 fb^{-1} of data, containing ~ 2.8 millions of B_s^0 mesons, have been analyzed at the energy of the $\Upsilon(5S)$ resonance ($\sqrt{s} \approx 10.87$ GeV).

The $\Upsilon(5S)$ resonance is above the $B_s^0\bar{B}_s^0$ threshold and it was naturally expected that the B_s^0 meson could be studied as well as the B mesons are studied with $\Upsilon(4S)$ data. The large potential of such $\Upsilon(5S)$ data was quickly confirmed [3, 4] with the 2005 engineering run representing 1.86 fb^{-1}. The main advantage with respect to the hadronic colliders is the possibility of measurements of absolute branching fractions. However, the abundance of B_s^0 mesons in $\Upsilon(5S)$ hadronic events has to be precisely determined. Above the $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ continuum events, the $e^+e^- \to b\bar{b}$ process can produce different kinds of final states: seven with a pair of non-strange B mesons ($B^*\bar{B}^*$, $B^*\bar{B}$, $B\bar{B}$, $B^*\bar{B}^*\pi$, $B^*\bar{B}\pi$, $B\bar{B}\pi$ and $B\bar{B}\pi\pi$) and three with a pair of B_s^0 mesons ($B_s^*\bar{B}_s^*$, $B_s^*\bar{B}_s^0$ and $B_s^0\bar{B}_s^0$) since the B^* and B_s^* mesons always decay by emission of a photon. The total $e^+e^- \to b\bar{b}$ cross section at the $\Upsilon(5S)$ energy was measured to be $\sigma_{b\bar{b}}^{\Upsilon(5S)} = (302 \pm 14)$ pb [3, 5] and the fraction of B_s^0 events to be $f_s = \sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})/\sigma_{b\bar{b}}^{\Upsilon(5S)} = (19.3 \pm 2.9)$ % [6]. The dominant B_s^0 production mode, $b\bar{b} \to B_s^*\bar{B}_s^*$, represents approximately 90% [7] of the $b\bar{b} \to B_s^{(*)}\bar{B}_s^{(*)}$ events. Published results on the $B_s^0 \to D_s^-\pi^+$ and $B_s^0 \to D_s^{\mp}K^{\pm}$ modes [7] and on the electromagnetic penguin decays

[1] Proceedings of a presentation at the Lake Louise Winter Institute 2009 (Alberta, Canada), 16–21 February 2009.

[2] The notation "B" refers either to a B^0 or a B^+. Moreover, charge-conjugated states are implied everywhere.

$B_s^0 \to \phi\gamma$ and $B_s^0 \to \gamma\gamma$ [8] are presented. Preliminary results about the $B_s^0 \to J/\psi\, K_S^0$ and $B_s^0 \to J/\psi\, \phi$ modes [9] and the semi-leptonic B_s^0 decays [10] are also described. In addition, recent results on bottomonium production are reported [11], including preliminary measurements obtained with the data from the energy scan performed near the $\Upsilon(5S)$ resonance [12].

For the exclusive modes, the B_s^0 candidates are fully reconstructed from the final-state particles. The signal is analyzed with the successful method developed at the B factories. From the reconstructed four-momentum in the CM $(E^*_{B_s^0}, p^*_{B_s^0})$, two variables are formed: the energy difference $\Delta E = E^*_{B_s^0} - \sqrt{s}/2$ and the beam-constrained mass $M_{\rm bc} = \sqrt{s/4 - p^{*2}_{B_s^0}}$. The signal yields are extracted from a two-dimensional fit performed of the distribution of these two variables. As the B_s^0 can be produced via three kinematically-different $\Upsilon(5S)$ decays[3], we expect three signal regions in the $(M_{\rm bc}, \Delta E)$ plane. The location of these regions (two observables per region) can be related to the B_s^* and B_s^0 masses, providing a measurement of these two interesting physical parameters.

The flavour-specific $B_s^0 \to D_s^-\pi^+$ mode proceeds dominantly via a tree amplitude. Its Cabibbo-suppressed counterpart, $B_s^0 \to D_s^\mp K^\pm$, is not flavour-specific and is therefore interesting for CP-violation studies. The dominant $B_s^0 \to D_s^-\pi^+$ mode is a good candidate for a normalization channel at hadron colliders thanks to its clean signature (four charged tracks) and its large branching fraction. The D_s^- mesons are reconstructed via three channels: $D_s^- \to \phi(\to K^+K^-)\pi^-$, $D_s^- \to K^{*0}(\to K^+\pi^-)K^-$ and $D_s^- \to K_S^0(\to \pi^+\pi^-)K^-$. The selected candidates are shown in Fig. 1.

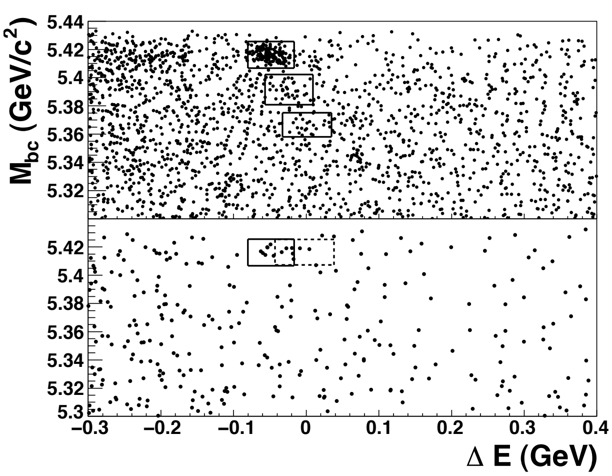

Figure 1. $B_s^0 \to D_s^-\pi^+$ (top) and $B_s^0 \to D_s^\mp K^\pm$ (bottom) candidates selected in 23.6 fb^{-1} and represented in the $(M_{\rm bc}, \Delta E)$ plane. On the top plot, the three boxes represent the 2.5σ regions where B_s^0 candidates from $\Upsilon(5S) \to B_s^*\bar{B}_s^*$, $B_s^*\bar{B}_s^0$, $B_s^0\bar{B}_s^0$ modes (from left to right) are expected. On the bottom plot, the solid box represents the signal region, while the dashed box shows the location of $B_s^0 \to D_s^-\pi^+$ decays when the pion is misidentified as a kaon; both boxes are for the $\Upsilon(5S) \to B_s^*\bar{B}_s^*$ mode only.

From the fitted $B_s^0 \to D_s^-\pi^+$ yields and peak positions in the three signal regions, we measure six parameters: $\mathcal{B}(B_s^0 \to D_s^-\pi^+) = [3.67^{+0.35}_{-0.33}({\rm stat.})^{+0.43}_{-0.42}({\rm syst.}) \pm 0.49(f_s)] \times 10^{-3}$, $f_{B_s^*\bar{B}_s^*} = N_{B_s^*\bar{B}_s^*}/N_{B_s^{(*)}\bar{B}_s^{(*)}} = \left(90.1^{+3.8}_{-4.0} \pm 0.2\right)\%$, $f_{B_s^*\bar{B}_s^0} = N_{B_s^*\bar{B}_s^0}/N_{B_s^{(*)}\bar{B}_s^{(*)}} = \left(7.3^{+3.3}_{-3.0} \pm 0.1\right)\%$, $f_{B_s^0\bar{B}_s^0} = N_{B_s^0\bar{B}_s^0}/N_{B_s^{(*)}\bar{B}_s^{(*)}} = \left(2.6^{+2.6}_{-2.5}\right)\%$, $m_{B_s^0} = (5364.4 \pm 1.3 \pm 0.7)$ MeV/c^2 and $m_{B_s^*} = (5416.4 \pm 0.4 \pm 0.5)$ MeV/c^2. For the $B_s^0 \to D_s^\mp K^\pm$ candidates, we fit a signal only in the $B_s^*\bar{B}_s^*$ region as 90% of the events are concentrated there. A 3.5σ evidence with $6.7^{+3.4}_{-2.7}$ events is obtained, leading to the branching fraction $\mathcal{B}(B_s^0 \to D_s^\mp K^\pm) = [2.4^{+1.2}_{-1.0}({\rm stat.}) \pm 0.3({\rm syst.}) \pm 0.3(f_s)] \times 10^{-4}$.

The dominant process leading to the $B_s^0 \to \phi\gamma$ and $B_s^0 \to \gamma\gamma$ decays is an electromagnetic radiative penguin diagram. The $b \to s\gamma$ transitions are an important test for the standard model

[3] In this context, the notation "$\Upsilon(5S)$" stands for any produced $b\bar{b}$ pair, including non-resonant $b\bar{b}$ continuum since it is not distinguishable from the resonant $\Upsilon(5S)$ state.

(SM). We obtain the first observation (5.5σ) with 18^{+6}_{-5} events (Fig. 2), leading to the branching fraction $\mathcal{B}(B_s^0 \to \phi\gamma) = (57^{+18+12}_{-15-11}) \times 10^{-6}$. This is the first observation of a radiative B_s^0 decay. We don't have enough statistics to see a significant $B_s^0 \to \gamma\gamma$ excess (Fig. 3). We set, at 90% C.L., an upper limit $\mathcal{B}(B_s^0 \to \gamma\gamma) < 8.7 \times 10^{-6}$, which is six times more stringent than the previous limit and only one order of magnitude larger than the SM prediction.

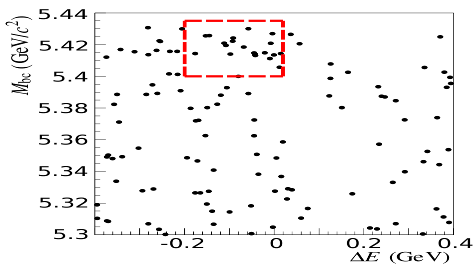

Figure 2. Selected $B_s^0 \to \phi\gamma$ candidates. The box is the 2.5σ region where the signal is expected for the $\Upsilon(5S) \to B_s^* \bar{B}_s^*$ mode.

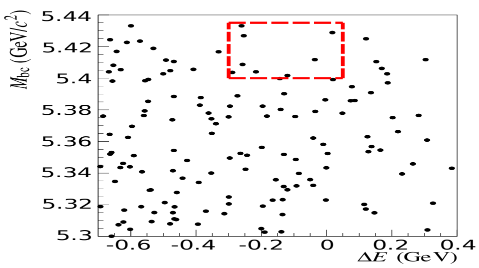

Figure 3. Selected $B_s^0 \to \gamma\gamma$ candidates. The box is the 2.5σ region where the signal is expected for the $\Upsilon(5S) \to B_s^* \bar{B}_s^*$ mode.

A search for the $B_s^0 \to J/\psi\, \phi$ decay (and the Cabibbo-suppressed $B_s^0 \to J/\psi\, K_S^0$ decay) has been performed (Fig. 4). The leading contribution comes from the colour-suppressed $b \to c\bar{c}s$ ($c\bar{c}d$) spectator diagram, but a penguin loop may also contribute. While no significant signal is seen for the $B_s^0 \to J/\phi\, K_S^0$ mode, the observation of ~ 45 events for the $B_s^0 \to J/\psi\, \phi$ mode leads to the first absolute measurement of the branching fraction $\mathcal{B}(B_s^0 \to J/\psi\, \phi) = (1.15^{+0.28}_{-0.30}) \times 10^{-3}$.

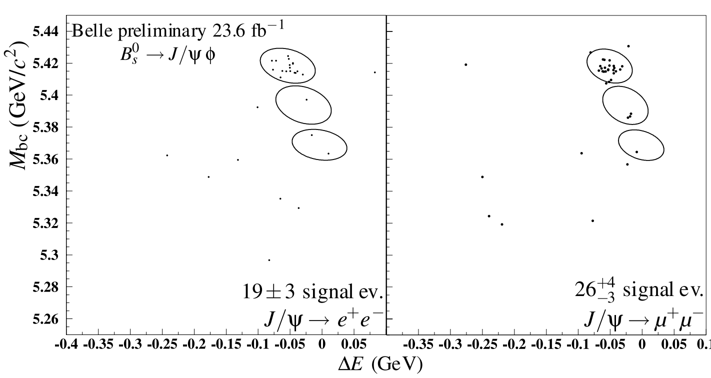

Figure 4. Selected $B_s^0 \to J/\phi\, \phi$ candidates. The left (right) plot presents candidates with the J/ϕ decaying to electrons (muons). The elliptic regions have the same meaning as the boxes in the top plot of Fig. 1.

The inclusive semi-leptonic branching fractions of the B_s^0 meson have been measured thanks to its fast particle-antiparticle oscillation: by requiring events with a fully reconstructed $D_s^- \to \phi(\to K^+K^-)\pi^-$ and a fast lepton with the same sign, only events with a $B_s^0\bar{B}_s^0$ pair are selected, After a fit of the lepton CM momentum to disentangle primary and secondary leptons, the results obtained are $\mathcal{B}(B_s^0 \to X^+\, e^-\, \nu) = (10.9 \pm 1.0 \pm 0.9)\%$ and $\mathcal{B}(B_s^0 \to X^+\, \mu^-\, \nu) = (9.2 \pm 1.0 \pm 0.8)\%$. The average is $\mathcal{B}(B_s^0 \to X^+\, l^- \nu) = (10.2 \pm 0.8 \pm 0.9)\%$, in good agreement with $\mathcal{B}(B^0 \to X^+\, l^- \nu)$ [6] which is expected to be very similar.

Not only B_s^0 mesons can be studied with $\Upsilon(5S)$ data. A search for bottomonium production ($\Upsilon(nS)$, $n = 1, 2, 3$), based on the full reconstruction of $\Upsilon(5S) \to \Upsilon(nS)(\to \mu^+\mu^-)\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(nS)(\to \mu^+\mu^-)K^+K^-$ decays, showed rates about two order of magnitude larger than expected from $\Upsilon(4S)$ rates. A six-point energy scan near the $\Upsilon(5S)$ resonance has been performed to study the variation of these rates as function of $\sqrt{s}$. On Fig. 5, a clear difference between the inclusive hadronic line shape ($m = 10865 \pm 8$ MeV/c^2, $\Gamma = 110 \pm 13$ MeV) and the exclusive bottomonium-production line shape ($m = 10889.6 \pm 2.3$ MeV/c^2, $\Gamma = 54.7^{+8.9}_{-7.6}$ MeV) can be seen. While the former is compatible with previous CLEO and CUSB measurements [13, 14], the latter is shifted by $+(24.6 \pm 8.3)$ MeV/c^2 and twice narrower. An interpretation could be a new Y_b state with small production cross section and large branching fraction to the $\Upsilon(nS)\pi\pi$ final state. However the Babar collaboration has recently measured [15] an inclusive line shape with a width twice smaller than Belle. The result of an exclusive analysis by Babar would be very welcome to help clarifying the situation.

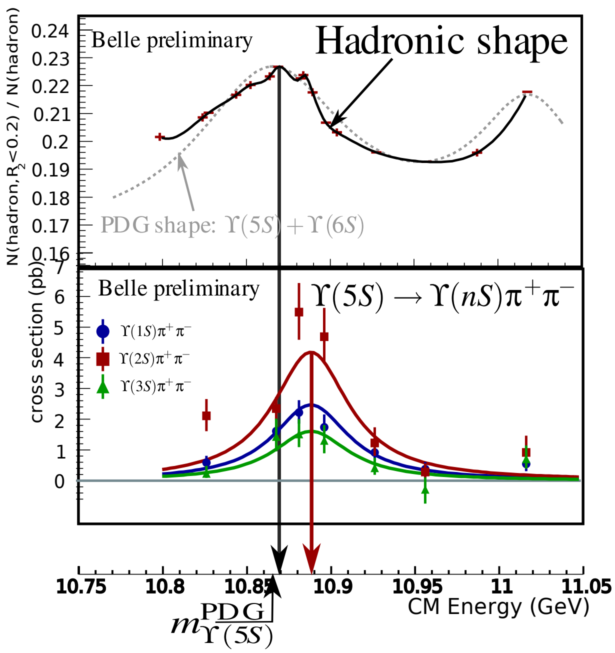

Figure 5. Hadronic production (top) and $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ cross section (bottom) as a function of $\sqrt{s}$. On the top plot, the grey dashed line is the shape of the $\Upsilon(5S)$ and $\Upsilon(6S)$ as present in Ref. [6]. On the bottom plot, the three sets of points, representing $\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$ (circle, blue), $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ (square, red) and $\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$ (triangle, green) data, are fitted with the same Breit-Wigner shape.

To conclude, all these studies demonstrate the great potential of the Belle dataset recorded at $\Upsilon(5S)$ energy. The sensitivity obtained for several B_s^0 modes allows many interesting measurements, from B_s^0 physical parameters to searches for new physics. Besides that, the intriguing measurements of the $\Upsilon(5S) \to \Upsilon(nS)h^+h^-$ channels open a new interest in bottomonium spectroscopy. So far, the full Belle sample has reached 65 fb^{-1}, and the KEKB collider will continue delivering collisions at the $\Upsilon(5S)$ energy during 2009. Of course, many more interesting results are expected with the full Belle $\Upsilon(5S)$ dataset.

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