Study of Transitions and Decays of Bottomonia at Belle

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We review the studies of transitions and decays of bottomonium states from the e^+e^- data recorded by the Belle detector at various Υ resonances. We also report a recent study of the branching fractions of $\chi_{bJ}(1P)$ to 41 hadronic final states in the $\Upsilon(2S)$ data sample. In the same study, a 90% confidence-level upper limit is set for the first time on the width of $\chi_{b0}(1P)$ at $\Gamma_{\text{total}} < 2.4\,\text{MeV}$.

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1. Introduction

Bottomonium, a bound system of a bottom (b) quark and its antiquark ($\bar{b}$), offers a unique laboratory to study the strong interaction; since the b quark is heavier than other quarks ($q = u, d, s, c$), the system can be described by non-relativistic quantum mechanics and effective theories [1].

The typical radius of the bottomonium from the potential model is of the order of $10^{-1} fm$, and with such a small radius the idea of multipole expansion (widely used in electrodynamics) can be applied to the soft gluon emissions in hadronic transitions between different bottomonium states [2]. In the case of radiative transitions, the wavelength of the photon is larger (atmost comparable) to the size of radiating system hence dipole transitions dominate.

This proceeding presents a review of studies of radiative and hadronic transitions between various bottomonium states as well as their decays to several hadronic final states, based on the data recorded with the Belle detector located at the KEKB asymmetric-energy e^+e^- collider. The $\Upsilon(nS)$ states have $J^{PC} = 1^{--}$, hence it can be directly produced in the e^+e^- collisions when the total center-of-mass (CM) energy is close to the resonance mass. Other bottomonium states are mostly originate from the $\Upsilon(nS)$ decays.

2. Dipion transitions from $\Upsilon(5S)$

The Belle Collaboration observed two orders of magnitude larger partial width of the dipion transition $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(mS)$, where $m = 1$, 2 and 3 than the corresponding partial widths from $\Upsilon(4S)$, $\Upsilon(3S)$, or $\Upsilon(2S)$ [3]. The dipion transition from $\Upsilon(5S)$ via intermediate $B^{(*)}\bar{B}^{(*)}$ re-scattering can explain this large branching fraction [4]. Another interesting result in this transition from $\Upsilon(5S)$ was the first observation of $h_b(1,2P)$ [5]. In that analysis, Belle observed that cross-sections of the processes $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(2S)$ and $\Upsilon(5S) \to \pi^+\pi^-h_b(1,2P)$ are of comparable magnitude, as shown in Figure 1. Such a large rate was unexpected because production of $h_b(1,2P)$ requires a b-quark spin flip, while that of $\Upsilon(2S)$ does not. This indicates that the production of $h_b(1,2P)$ at $\Upsilon(5S)$ must occur via a process that mitigates the expected suppression related to heavy quark spin, which subsequently led to the observation of two charged bottomoniumlike resonances [6].

3. Radiative transitions from $h_b(1,2P)$

A 133.4 fb^{-1} of data sample collected near the $\Upsilon(5S)$ resonance is used to study the process $e^+e^- \to \Upsilon(5S) \to h_b(nP)\pi^+\pi^-, h_b(nP) \to \eta_b(mS)\gamma$ for $n \geq m = 1$ and 2, in which the $\eta_b(mS)$ states are not exclusively reconstructed [7]. In this analysis, Belle reported the first evidence for the $\eta_b(2S)$ as well as the most precise mass measurement of $\eta_b(1S)$ and its width for the first time. To identify signal events, only a photon and $\pi^+\pi^-$ pair are reconstructed and a missing mass against $\Upsilon(5S)$ is defined as $M_{miss}(X) = \sqrt{(E_{CM} - E_X^\star)^2 - p_X^{\star 2}}$, where E_{CM} is the CM energy, and E_X^* and p_X^* are the energy and momentum of the recoiling system X measured in the CM frame. The missing mass against the dipion system, $M_{miss}(\pi^+\pi^-)$, is used in selecting $h_b(nP)$ signal events, while the $\eta_b(mS)$ signal is identified with the variable, $M_{miss}^{(n)}(\pi^+\pi^-\gamma) = M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + m_{h_b(nP)}$. The $h_b(nP)$ yield *vs.* $M_{miss}^{(n)}(\pi^+\pi^-\gamma)$ distribution is shown in Figure 2 (left plots), where the peak near 9.4 GeV/c^2 is identified as the $\eta_b(1S)$. The mass of the $\eta_b(1S)$ state is measured as
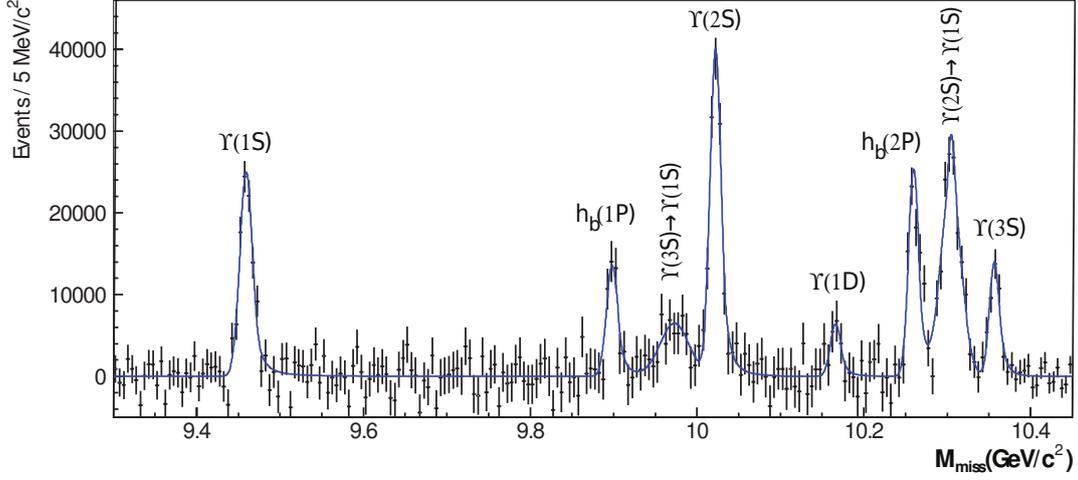
Figure 1: Missing mass spectrum against the dipion system in the data recorded with Belle at the $\Upsilon(5S)$ resonance. The plot is taken from Ref. [5].

$9402.4 \pm 1.5 \pm 1.8$ MeV/c^2, which corresponds to the hyperfine splitting of $[\Delta M_{HF}(1S)]$ 57.9 ± 2.3 MeV/c^2. The $\eta_b(1S)$ width is also measured in the same analysis and found to be $10.8^{+4.0+4.5}_{-3.7-2.0}$ MeV.

The $h_b(2P)$ yield *vs.* $M^{(2)}_{miss}(\pi^+\pi^-\gamma)$ distribution is shown in Figure 2 (right), where the peak near 10.0 GeV/c^2 is identified as the $\eta_b(2S)$. The significance of the $\eta_b(2S)$ signal is 4.2σ and its mass is $9999.0 \pm 3.5^{+2.8}_{-1.9}$ MeV/c^2, which corresponds to a hyperfine splitting for 2S, $\Delta M_{HF} = 24.3^{+4.0}_{-4.5}$ MeV/c^2.

4. Radiative transitions from $\Upsilon(2S)$

The data for 158×10^6 $\Upsilon(2S)$ decays recorded with the Belle detector have been used to study the radiative population of states reconstructed from 26 different exclusive hadronic final states [8]. This analysis was done with the motivation to search for a bottomonium state near 9975 MeV/c^2, $X_{b\bar{b}}(9975)$, claimed to have been observed in the radiative $\Upsilon(2S)$ decays recorded by the CLEO detector [9]. We found no evidence for an $X_{b\bar{b}}(9975)$ signal. The reconstructed invariant mass of the $b\bar{b}$ system is presented in terms of $\Delta M \equiv M[(b\bar{b})\gamma] - M(b\bar{b})$, and result of the fit to the data is shown in Figure 3. A 90% CL upper limit is determined on the product branching fraction $\mathscr{B}[\Upsilon(2S) \to X_{b\bar{b}}(9975)\gamma] \times \sum_i \mathscr{B}[X_{b\bar{b}}(9975) \to h_i] < 4.9 \times 10^{-6}$, which is an order of magnitude smaller than that reported in Ref. [9].

The disconfirmation of the $X_{b\bar{b}}(9975)$ state was extremely important as the claim that it is the $\eta_b(2S)$ state was in disagreement with theory predictions and the Belle result [7]. We have also searched for the $\eta_b(1S)$ state and set an upper limit $\mathscr{B}[\Upsilon(2S) \to \eta_b(1S)\gamma] \times \sum_i \mathscr{B}[\eta_b(1S) \to h_i] < 3.7 \times 10^{-6}$ at 90% CL. A large signal yield is observed for $\chi_{bJ}(1P)$ states from the sum of 26 exclusive hadronic final states, in the same analysis. The yields for $\chi_{bJ}(1P)(J = 0, 1, 2)$ were 299 ± 22, 946 ± 36 and 582 ± 31, respectively.
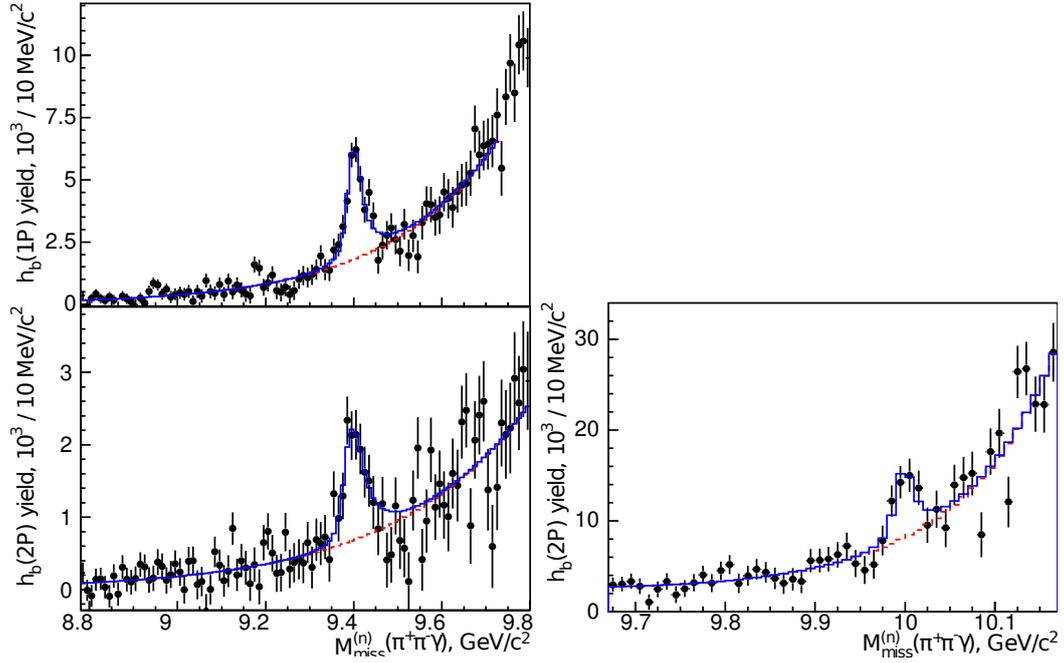
Figure 2: $h_b(1P)$ yield *vs.* $M_{miss}^{(1)}(\pi^+\pi^-\gamma)$ (top-left), and $h_b(2P)$ yield *vs.* $M_{miss}^{(2)}(\pi^+\pi^-\gamma)$ distribution in the $\eta_b(1S)$ (bottom-left) and $\eta_b(2S)$ (bottom-right) regions. Points with error bars are the data, blue solid histograms are the result from a fit, and the red dashed histograms are the background component of the fit. The plot is taken from Ref. [7].
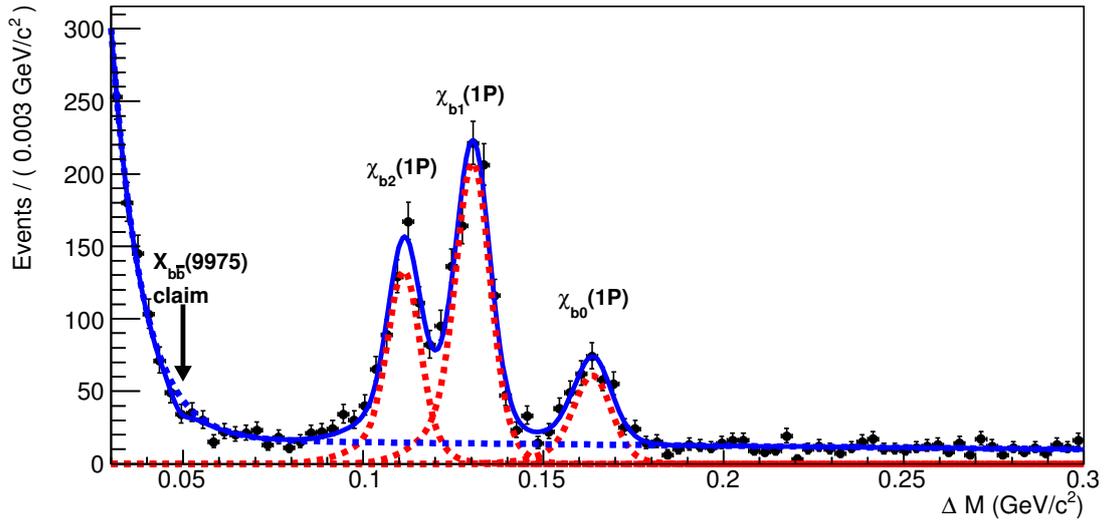
Figure 3: ΔM distributions for $\Upsilon(2S)$ data events. Points with error bars are the data, the blue solid curve is the result of the fit for the signal-plus-background hypothesis, and the blue dashed curve is the background component. The plot is taken from Ref. [8].

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5. $\chi_{bJ}(1P)$ **decays to light hadrons**

The analysis mentioned in the Section 4 motivated a study of the product branching fractions $\mathscr{B}[\Upsilon(2S) \to \gamma\chi_{bJ}(1P)] \times \mathscr{B}[\chi_{bJ}(1P) \to h_i]$, where h_i is a specific hadronic mode; such decays of $\chi_{bJ}(1P)$ mesons give us insight into how initial quarks and gluons hadronize [10]. We performed this study using the same $\Upsilon(2S)$ datasets with the $\chi_{bJ}(1P)$ being copiously produced from the $\Upsilon(2S)$ via electric dipole radiative transitions. The $\chi_{bJ}(1P)$ states can decay to many hadronic final states. For decays into all-charged final states, we focus on the same 26 modes as in Ref. [8]. In addition, modes with one π^0 and two π^0's are added to the mentioned final states excluding $2(\pi^+\pi^-)\pi^0$, $3(\pi^+\pi^-)\pi^0$, $4(\pi^+\pi^-)\pi^0$ and $5(\pi^+\pi^-)\pi^0$ as those are forbidden by G-parity conservation). In total, 74 light hadronic decay modes of the $\chi_{bJ}(1P)$ are reconstructed. A detailed analysis procedure of this study is mentioned in Ref. [11].

The result of the likelihood fit to the ΔM ($\Delta M \equiv M[\chi_{bJ}(1P)\gamma] - M[\chi_{bJ}(1P)]$) distribution for the sum of 74 modes in data is shown in Figure 4. The masses of the $\chi_{bJ}(1P)(J = 0, 1, 2)$ states obtained are in good agreement with their world average values [12].
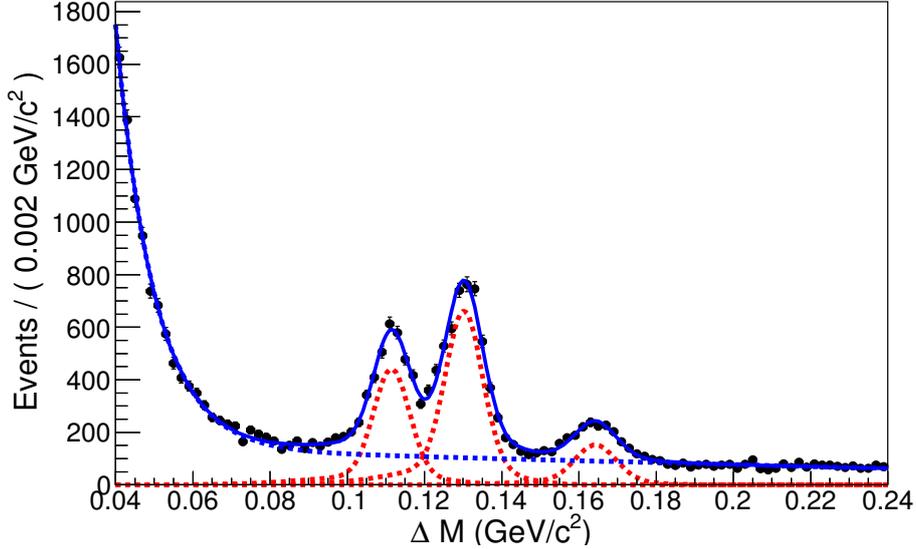
Figure 4: ΔM distribution in the $\Upsilon(2S)$ data. The three $\chi_{bJ}(1P)$ ($J = 0, 1$, and 2, respectively from right to left) components are indicated by the red dashed curves. The plot is taken from Ref. [11]

In total, 41 modes have above 5 standard deviation (σ) significance in at least one of the $\chi_{bJ}(1P)(J = 0, 1, 2)$ signals. Our branching fraction results are consistent with, and more precise than, reported in a similar analysis performed in data collected by the CLEO III detector [13]. Furthermore, a $\chi_{bJ}(1P)$ signal for $J = 0, 1$, and 2 has been observed for the first time in 9, 27, and 16 modes, respectively. And, we also found first evidence of a $\chi_{bJ}(1P)$ signal in 18, 1, and 14 modes for $J = 0, 1$, and 2, respectively.

The large signal yield obtained in our branching fraction studies of the $\chi_{bJ}(1P)$ triplet motivates a width measurement of the $\chi_{b0}(1P)$. The $\chi_{b0}(1P)$ width is found to be 1.3 ± 0.9 MeV. In the absence of a statistically significant result, we derive an upper limit on the width of the $\chi_{b0}(1P)$ < 2.4 MeV at 90% CL.

6. η transition from $\Upsilon(4S)$

As mentioned in Section 1, hadronic transitions between the lower mass quarkonium levels can be described using the QCD mulitpole expansion. The $\pi\pi$ and η transitions between the vector states proceed via emission of $E1E1$ and $E1M2$ gluons, respectively. Therefore, the η transitions are highly suppressed as they require a spin flip of the heavy quark [14]. The ratio of branching fractions:

$$\mathscr{R}_{\pi\pi S}^{\eta S}(n,m) = \frac{\mathscr{B}[\Upsilon(nS) \to \eta\Upsilon(mS)]}{\mathscr{B}[\Upsilon(nS) \to \pi^+\pi^-\Upsilon(mS)]}$$

is measured to be small for low-lying states: $\mathscr{R}_{\pi\pi S}^{\eta S}(2,1) = (1.64 \pm 0.23) \times 10^{-3}$ [15, 16, 17] and $\mathscr{R}_{\pi\pi S}^{\eta S}(3,1) < 2.3 \times 10^{-3}$ [16].

Above the $B\bar{B}$ threshold, BaBar unexpectedly observed the transition $\Upsilon(4S) \to \eta\Upsilon(1S)$ with a large branching fraction of $(1.96 \pm 0.28) \times 10^{-4}$, corresponding to $\mathscr{R}_{\pi\pi S}^{\eta S}(4,1) = 2.41 \pm 0.42$ [18]. This apparent violation of the heavy quark spin-symmetry was explained by the contribution of B meson loops or, equivalently, by the presence of a four-quark $B\bar{B}$ component inside the $\Upsilon(4S)$ wave function [19, 20]. At the $\Upsilon(5S)$ energy, the anomaly is even more striking. The spin-flipping processes $\Upsilon(5S) \to \pi\pi h_b(1P, 2P)$ have been found not to be suppressed with respect to the spin-symmetry preserving reactions $\Upsilon(5S) \to \pi\pi\Upsilon(1S, 2S)$ [5], and all the $\pi\pi$ transitions showed the presence of new resonant structures [21, 22] that cannot be explained as conventional bottomonium states.

Further insight into the mechanism of the hadronic transitions above the threshold can be gained by searching for the $E1M1$ transition $\Upsilon(4S) \to \eta h_b(1P)$, which is predicted to have a branching fraction of the order of 10^{-3} [23]. The missing mass spectrum of η meson, $M_{\mathrm{miss}}(\eta) = \sqrt{(p_{e^+e^-} - p_\eta)^2}$, where $p_{e^+e^-}$ and p_η are, respectively, the four-momenta of the colliding e^+e^- pair and the η meson, is investigated in the 772×10^6 $\Upsilon(4S)$ decays collected by Belle [24]. Figure 5 shows the background-subtracted $M_{\mathrm{miss}}(\eta)$ distribution, where the transition $\Upsilon(4S) \to \eta h_b(1P)$ is observed for the first time with a statistical significance of 11σ. The branching fraction of the transition, $\mathscr{B}[\Upsilon(4S) \to \eta h_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$, is in agreement with the theoretical prediction [23].

In the same analysis, the $\eta_b(1S)$ is also studied by reconstructing the transitions $\Upsilon(4S) \to \eta h_b(1P) \to \eta\gamma\eta_b(1S)$. The $\eta_b(1S)$ signal is observed with a statistical significance of 9σ, which allowed us to measure its mass $9400.7 \pm 1.7 \pm 1.6 \,\mathrm{MeV}/c^2$ and width, $\Gamma_{\eta_b(1S)} = (8^{+6}_{-5} \pm 5)\,\mathrm{MeV}$.

7. $\Upsilon(1,2S)$ decays to $\Lambda\bar{\Lambda}$

The inclusive production rate of Λ has been found to be three times larger in the $\Upsilon(1S)$ annihilation with respect to the nonresonant $e^+e^- \to q\bar{q}$ events at the same CM energy [25]. An analysis is performed in the $\Upsilon(1S)$ and $\Upsilon(2S)$ datasets collected with the Belle detector to study the exclusive production of hyperons or, specifically $\Lambda\bar{\Lambda}$ pair. The $\Upsilon(1S)$ and $\Upsilon(2S)$ are reconstructed in 48 final states comprising a $\Lambda\bar{\Lambda}$, up to three $p\bar{p}$, K^+K^- or $\pi^+\pi^-$ pairs, and one π^0.

In total, we observe 16 $\Upsilon(1S)$ and 7 $\Upsilon(2S)$ annihilation modes with a $\Lambda\bar{\Lambda}$ pair. Furthermore, we concluded that the $\Lambda\bar{\Lambda}$ production occurs mostly in high multiplicity environment. Also, shown in Figure 6, the branching fraction scales with the increasing number of additional particles.
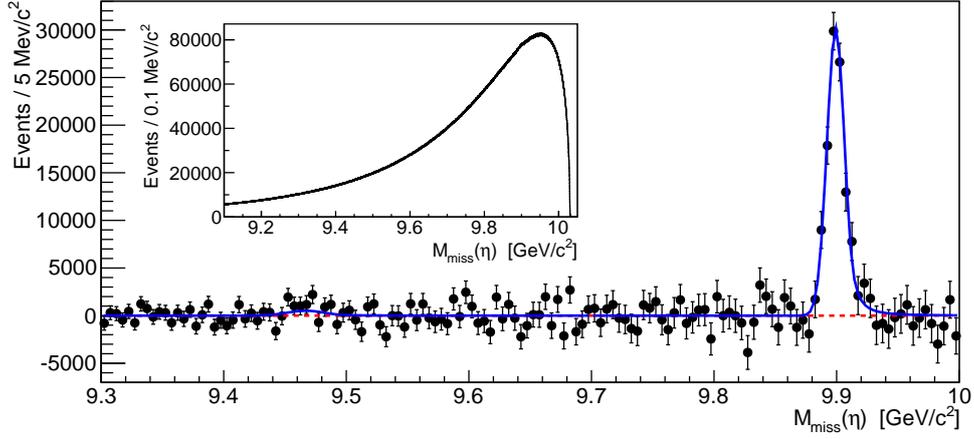
Figure 5: $M_{\mathrm{miss}}(\eta)$ distribution after the background subtraction. The blue solid curve shows the fit with the signal PDFs, while the red-dashed line represents the background only hypothesis. The inset shows the $M_{\mathrm{miss}}(\eta)$ distribution before the background subtraction. The plot is taken from Ref. [24]
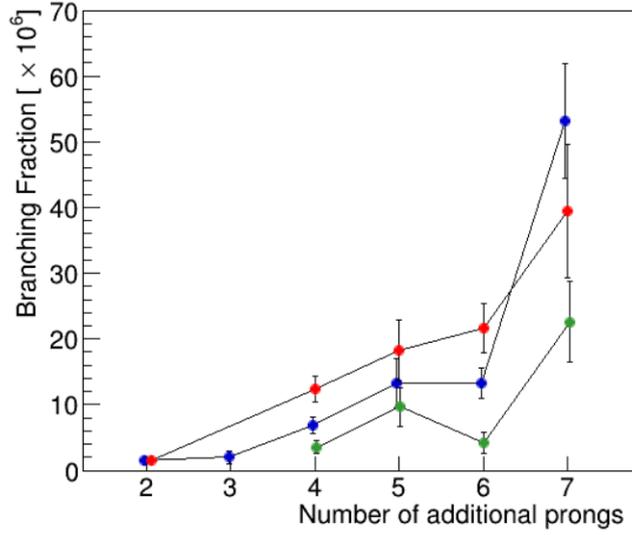
Figure 6: Branching fraction of $\Upsilon(1S) \to \Lambda\bar{\Lambda} + n\pi$ (red dots), $\Upsilon(2S) \to \Lambda\bar{\Lambda} + n\pi$ (green dots) and $\Upsilon(1S) \to \Lambda\bar{\Lambda}K^+K^- + (n-2)\pi$ (blue dots) as a function of total number of mesons (n) produced in association with the $\Lambda\bar{\Lambda}$ pair.

8. Summary

It was an exciting decade for heavy quarkonium physics especially at the Belle experiment, with discoveries of a number of conventional and non-conventional bottomonium states. In this proceeding, only few recent interesting results of transitions and decays of bottomonium have been summarized. We also reported a recent study of the branching fractions of $\chi_{bJ}(1P)$ to several hadrons in the $\Upsilon(2S)$ data sample. In the same study a 90% CL upper limit is set on the width of $\chi_{b0}(1P)$ at $\Gamma_{\mathrm{total}} < 2.4\,\mathrm{MeV}$.

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