PROCEEDINGS OF SCIENCE

Properties of non-$q\bar{q}$ XYZ mesons and results of a search for the H-dibaryon

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A number of charmonium- and bottomonium-like meson states have been observed that have properties that do not match well to expectations for the simple quark-antiquark substructure suggested by the constituent quark model. Some of them are electrically charged and decay to final states containing hidden charmonum or bottomonium mesons and, thus, must contain at least four quarks. Common properties of these so-called XYZ mesons are partial widths for decays to hidden quarkonium states plus light hadrons that are much larger than corresponding partial widths for established quarkonium mesons. I review some recent results from the Belle experiment, including the recent discovery of two charged bottomium-like states, the $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$, that decay to $\pi^{\pm}h_b(mS)$ $(m = 1,2)$ and $\pi^{\pm}\Upsilon(nS)$ $(n = 1,2,3)$ final states. In addition, I present recent Belle results from a search for H-dibaryon production in inclusive $\Upsilon(1S)$ and $\Upsilon(2S)$ decays.

International Winter Meeting on Nuclear Physics,
21-25 January 2013
Bormio, Italy

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1. Introduction

According to the prescriptions of the original quark model proposed by Gell-Mann [1] and Zweig [2] in 1964, mesons are comprised of quark-antiquark pairs and baryons are three-quark triplets. In the 1970's, this simple model was superseded by Quantum Chromodynamics (QCD), which identified the reason for these rules was that $q\bar{q}$ pairs and qqq combinations can be color singlet representations of the color $SU(3)$ group that is fundamental to the theory. Somewhat suprisingly, the mesons are $q\bar{q}$ and baryons are qqq prescription still adequately describes the hadronic particle spectrum despite the existence of a number of other color-singlet quark and gluon combinations that are possible in QCD [3]. Considerable experimental efforts at searching for the predicted color-singlet $qqq\bar{q}q$ "pentaquark" baryons [4] and the doubly strange $udsuds$ H-dibaryon [5] have failed to come up with any unambiguous candidates for either state [6]. Although a few candidates for non-$q\bar{q}$ light hadron resonances have been reported [7] none have been generally accepted as established by the hadron physics community [8].

In recent years, however, the situation changed, beginning with the observation of the $X(3872)$ meson by Belle [9], the discovery of the $Y(4260)$ meson by BaBar [10], and the subsequent observation of a number of other candidate charmonium-like meson states, the so-called XYZ mesons, that are not well matched to expectations for the quark-antiquark meson picture [11]. Here I give a brief report on why we think the observed states may be exotic and describe some recent observations of charged quarkonium-like meson states that necessarily must have a minimal four-quark structure by Belle [12, 13, 14] and BESIII [15].

In 1977, Jaffe predicted the existence of The H-dibaryon, a doubly strange, six-quark structure ($uuddss$) with quantum numbers $I = 0$ and $J^P = 0^+$ and a mass that is $\simeq 80$ MeV below the $2m_\Lambda$ [5]. An $S = -2$, baryon-number $B = 2$ particle with mass below $2m_\Lambda$ would decay via weak interactions and, thus, be long-lived with a lifetime comparable to that of the Λ and negligible natural width.

Jaffe's specific prediction was ruled out by the observation of double-Λ hypernuclei events [18, 19, 20], especially the famous "Nagara" event that has a relatively unambiguous signature as a ${}^{6}_{\Lambda\Lambda}$He hypernucleus produced via Ξ^- capture in emulsion [19]. The measured $\Lambda\Lambda$ binding energy, $B_{\Lambda\Lambda} = 7.13 \pm 0.87$ MeV, establishes, with a 90% confidence level (CL), a lower limit of $M_H >$ 2223.7 MeV, severely narrowing the window for a stable H to the binding energy range $B_H \equiv 2m_\Lambda - M_H < 7.9$ MeV[1]

Although Jaffe's original prediction for a binding energy of $\simeq 81$ MeV has been ruled out, the theoretical case for an H-dibaryon with a mass near $2m_\Lambda$ continues to be strong and has been recently strengthened by lattice QCD calculations (LQCD) by the NPLQCD [21, 22] and HALQCD [23] collaborations that both find a bound H-dibaryon, albeit for non-physical values for the pion mass. NPLQCD's linear (quadratic) extrapolation to the physical pion mass gives $B_H = -0.2 \pm 8.0$ MeV (7.4 ± 6.2 MeV) [22]. Carames and Valcarce [24] recently studied the H with a chiral constituent model constrained by ΛN, ΣN, ΞN and $\Lambda\Lambda$ cross section data and find B_H values that are similar to the NPLQCD extrapolated values.

Numerous experimental searches have been made for an H-dibaryon-like state with mass near (above or below) the $2m_\Lambda$ threshold. Although some hints of a virtual $\Lambda\Lambda$ state was reported by a

[1] In this report I have taken the liberty of averaging asymmetric errors and combining statistical and systematic errors in quadrature. For actual measured values, please refer to the original papers.

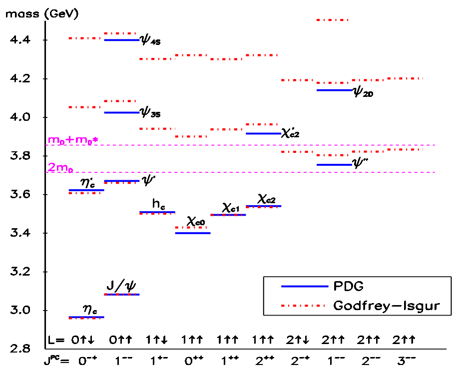

Figure 1: The charmonium meson spectrum. The solid bars indicate the established charmonium states and the dash-dot bars indicate the mass levels that were predicted in 1985.

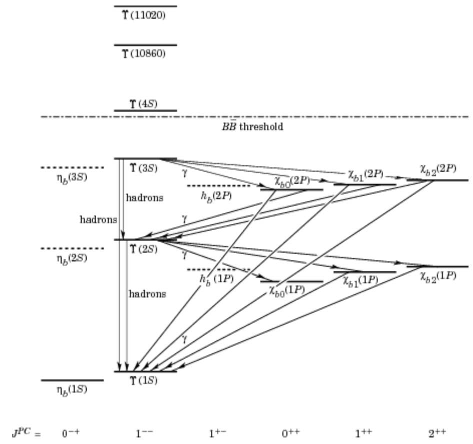

Figure 2: The bottomonium level diagram. The solid bars indicate well established states, in addition, candidates for the $h_b(1P)$, $h_b(2P)$ and $\eta_b(2S)$ states have recently been seen.

KEK experiment [25], other searches produced negative results [26, 27, 28, 29].

2. The Quarkonium Spectra

Quarkonium mesons, *i.e.*, mesons that contain a Q and $\overline{Q}$ quark pair, where Q is used to denote either the c- or b-quark, have proven to be useful probes for multiquark meson systems. That is because these mesons are well understood; their constituent quarks are non-relativistic and potential models can be applied. Most of the low-lying $Q\overline{Q}$ meson states have been discovered and found to have properties that agree reasonably well with potential model predictions. More complex states would likely have properties that deviate from model predictions and, thus, be identifiable as such.

Figure 1 shows a level diagram for the $c\bar{c}$ ("charmonium") system, where established states are indicated by solid lines, and the masses predicted by the Godfrey-Isgur (GI) relativized potential model in 1985 [16] are shown as dash-dot lines. All of the states below the $M = 2m_D$ open-charmed-meson threshold have been identified and have masses that agree reasonably well with GI predictions. Moreover, all of the above-threshold $J^{PC} = 1^{--}$ states below $M \simeq 4.45$ GeV have been assigned and, here too, there is reasonable agreement with predicted masses. In addition to the 1^{--} states, the χ'_{c2}, the 2^{++} radially excited $2\,^3P_2$ state, has been assigned [17] and Belle recently reported strong evidence for the ψ_2, the 2^{--} 1^3D_2 state [30]. Any meson state with prominent decays to final states containg a c- and a $\bar{c}$-quark, that does not fit into one of the remaining unassigned $c\bar{c}$ states has to be considered exotic.[2]

Figure 2 shows a level diagram for the $B\overline{B}$ ("bottomonium") system. Here all the levels indicated by solid bars are well established. In addition, the have been recently reported of the $h_b(1p)$, $h_b(2P)$ and $\eta_b(2S)$ [31, 32], as well as evidence for some of the (unshown) D-wave and $\chi_b(3P)$ states [33]. Three 1^{--} states above the $2m_B$ open-bottom threshold have been tentatively identified

[2]The large value of the c-quark mass precludes any substantial production of $c\bar{c}$ pairs via fragmentation processes.

as the $\Upsilon(4S)$, $\Upsilon(5S)$ and $\Upsilon(6S)$, and these are their commonly used names. The arrows in Fig. 2 indicate transitions between the sates accompanied by either light-hadron emission (vertical arrows) and $E1$ electromagnetic transitions (diagonal arrows). Not shown are the $\Upsilon(3S) \to \gamma\eta_b(1S)$ $M1$-transition that was used by BaBar to discover the $\eta_b(1S)$ [34], the $\Upsilon(5S) \to \pi^+\pi^- h_b(1P)$ and $\pi^+\pi^- h_b(2P)$ transitions used by Belle to discover the $h_b(1P,2P)$ states [31], or the $h_b(2P) \to \gamma\eta_b(2S)$ $E1$ transition that led to the discovery of the $\eta_b(2S)$ [32]. With the notable exception of the $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S,2S,3S)$ and $\Upsilon(5S) \to \pi^+\pi^- h_b(1S,2S)$ transitions, which are anomalously strong and discussed below, all of the other transitions have measured strengths that are consistent with theoretical expectations.

3. The $X(3872)$

The first XYZ meson that was observed is the $X(3872)$, which was seen as a pronounced peak in the $\pi^+\pi^- J/\psi$ invariant mass spectrum in exclusive $B^+ \to K^+\pi^+\pi^- J/\psi$ decays [9, 35]. Decays to $\gamma J/\psi$ [36, 37, 38], $\pi^+\pi^-\pi^0 J/\psi$ [36, 39], and $D^0\bar{D}^{*0}$ [40] have also been seen. The $\pi^+\pi^-$ invariant mass distribution in $X(3872) \to \pi^+\pi^- J/\psi$ decays is well described by the hypothesis that the pions originate from $\rho^0 \to \pi^+\pi^-$ decays [41, 42]. A CDF analysis of angular correlations among final state particles in $X(3872) \to \pi^+\pi^- J/\psi$ ruled out all possible J^{PC} assignments (for $J \leq 3$) other than 1^{++} and 2^{-+} [43]. A Belle analysis of angular correlations in $B \to KX(3872)$; $X(3872) \to \pi^+\pi^- J/\psi$ decays found good agreement with the 1^{++} hypotheses with no free parameters; for 2^{-+} there is one free complex parameter and a value for this was found that produces acceptable agreement with the measured data [42]. Recently, an comprehensive analysis of the five-dimensional angular correlations in the $B^+ \to K^+X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$ decay chain conclusively ruled out the 2^{-+} assignment and established, once and for all, that the J^{PC} of the $X(3872)$ is 1^{++} [44].

The only unassigned 1^{++} charmonium level with a predicted mass near 3872 MeV is the χ'_{c1}, the first radial excitation of the χ_{c1}. The assignment of the $X(3872)$ to this level has some problems. First, the mass is too low. Potential models predict the mass of the χ'_{c1} to be around 3905 MeV, where this is pegged to the measured mass of the multiplet-partner state $M_{\chi'_{c2}} = 3929 \pm 5$ MeV [17]. If the χ'_{c1} mass is $\simeq$3872 MeV, the χ'_{c2}-χ'_{c1} mass splitting would be $\simeq 57$ MeV, and higher than the χ_{c2}-χ_{c1} mass splitting of 45.5 ± 1.1 MeV. In potential models this splitting decreases with increasing radial quantum numbers [45]. Second, the decay $\chi'_{c1} \to \gamma\psi(2S)$ is a favored $E1$ transition and expected to be more than an order-of-magnitude stronger than "hindered" $E1$ transition $\chi'_{c1} \to \gamma J/\psi$ [46]. The Belle experiment recently reported a 90% CL limit on $\Gamma_{X(3872)\to\gamma\psi(2S)}$ that is less than $2.1 \times \Gamma_{X(3872)\to\gamma J/\psi}$ [36] and in contradiction with potential model expectations for the $X(3872) = \chi'_{c1}$ assignment. Third, the transition $\chi'_{c1} \to \pi^+\pi^- J/\psi$, the $X(3872)$ discovery mode, violates isospin and is expected to be strongly suppressed.

Two features of the $X(3872)$ that have attracted considerable attention are its narrow natural width, $\Gamma_{X(3872)} < 1.2$ MeV at the 90% CL [42], and its mass, for which (my) world average value is $M_{X(3872)} = 3871.67 \pm 0.17$ MeV, which is equal, to about a part in $\sim 10^4$, to the $D^0\bar{D}^{*0}$ mass threshold: $m_{D^0} + m_{D^{*0}} = 3871.79 \pm 0.30$ MeV.[47] The close proximity of the $M_{X(3872)}$ to the $D^0\bar{D}^{*0}$ threshold has led to speculation that the $X(3872)$ is a molecule-like D^0-$\bar{D}^{*0}$ bound state held together by nuclear-like π- and ω-meson exchange forces [48].

3.1 The $Y(4260)$

The $Y(4260)$ was seen by BaBar as a peak in the $M(\pi^+\pi^- J/\psi)$ distribution in the initial-state-radiation (ISR) process $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ [10], an observation that was confirmed by CLEO and Belle [49]. Since it is produced via the ISR process, its J^{PC} must be 1^{--}. In contrast to the $X(3872)$, the peak is relatively wide; the weighted average of the BaBar and Belle peak width measurements is $\Gamma_{Y(4260)} = 99 \pm 17$ MeV.

A striking feature of the $Y(4260)$ is that its peak mass is not near that of any of the established 1^{--} charmonium states. Moreover, since all 1^{--} charmonium states with mass below 4.45 MeV have been identified, the $Y(4260)$ cannot be a standard $c\bar{c}$ meson. Moreover, it does not seem to have a strong coupling to open-charm mesons; measurements of e^+e^- annihilation into charmed mesons in the vicinity of $\sqrt{s} \sim 4260$ MeV show indications of a dip in the total cross section at the location of the $Y(4260)$ peak [50]. This motivated a detailed analysis [51] that established a lower limit on the partial width $\Gamma_{Y(4260)\to\pi^+\pi^- J/\psi}$ that is greater than 1 MeV, which is huge for charmonium. The Belle group did a comprehensive search for $Y(4260)$ decays to all possible final states containing open charmed meson pairs and found no sign of a $Y(4260)$ signal in any of them [52]. Thus, it seems likely that the $\Gamma_{Y(4260)\to\pi^+\pi^- J/\psi}$ is substantially greater than 1 MeV. If this is the case, it would be a strong indication that some new, previously unanticipated, mechanism is involved.

Subsequent studies of the $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(2S)$ ISR process led to discoveries of states with similar characteristics decaying to the $\pi^+\pi^-\psi(2S)$ final state: the $Y(4360)$ by BaBar [53], and the $Y(4660)$ by Belle [54]. There is no evidence for open-charmed meson decays for either of these states. Moreover, there is no sign of them in the $\pi^+\pi^- J/\psi$ spectrum and is there no evidence for $Y(4260) \to \pi^+\pi^-\psi(2S)$.

4. Searches in the *b*-quark sector

The existence of the $Y(4260)$ and other 1^{--} hidden charm states with large partial widths to $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$ led to speculation that there may be counterparts in the *b*-quark sector [55]. This prompted a Belle measurement of the partial widths for $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1,2,3$). The expected branching fraction for these decays [55] is $\sim 10^{-5}$ and, with the data sample that was available at the time, the expectation was that no signal would be seen. (The measured branching fractions for the nearby $\Upsilon(4S)$ to $\pi^+\pi^-\Upsilon(nS)$ are less than 10^{-4} [47].) Rather remarkably, very strong signals were observed for all three decays modes, with branching fractions of nearly one percent — more than two-orders-of-magnitude times expectations [56]. In an attempt to determine whether or not the anomalous events were coming from decays of $\Upsilon(5S)$ or from some other, *b*-quark sector equivalent of the $Y(4260)$ lurking nearby, Belle did a cross section scan of $e^+e^- \to$ hadrons and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ [57] . This scan showed some indication that the $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ yield peaks at a mass distinct from that for $\Upsilon(5S) \to$ hadrons but with limited statistical significance (10888 ± 3 MeV for the three $\pi^+\pi^-\Upsilon(nS)$ channels *vs.* 10879 ± 3 MeV for inclusive hadrons).

4.1 Study of inclusive $\Upsilon(5S) \to \pi^+\pi^-$ plus anything

Motivated by the curious phenomena described in the preceding section, Belle made a study of the inclusive process $\Upsilon(5S) \to \pi^+\pi^-$ plus *anything* [31]. Figure 3 shows the missing mass recoiling against every $\pi^+\pi^-$ pair in events in a 121 fb^{-1} data sample collected at an e^+e^- c.m. energy in the vicinity of the $\Upsilon(5S)$ resonance. In this plot there are a huge number of entries, on the order of a million in each of the 1 MeV bins; the relative statistical error on each point is of order 0.1%. The distribution is fitted piecewise to a polynomial background shape plus signal peaks for all of the bottomonim states (and reflections) that are expected to be produced via this process.

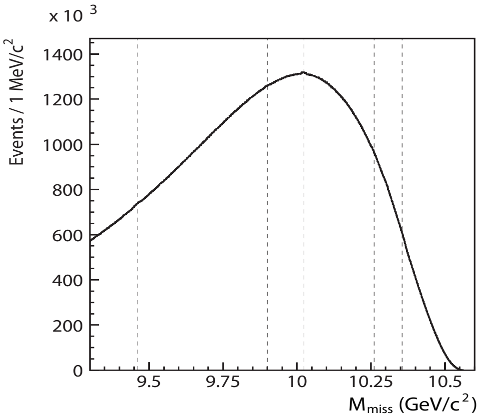

Figure 3: The mass of the system recoiling against the π^+ and π^- in inclusive $\Upsilon(5S) \to \pi^+\pi^-$ X decays. The dashed lines indicate the positions of the $\Upsilon(1S)$, $h_b(1P)$, $\Upsilon(2S)$, $h_b(2P)$ and $\Upsilon(3S)$.

Figure 4 shows the results of the fit with the background component subtracted. There, in addition to peaks corresponding to $\pi^+\pi^-\Upsilon(nS)$ $(n = 1,2,3)$ and reflections from the ISR processes $e^+e^- \to \gamma_{ISR}\Upsilon(mS)$, $\Upsilon(mS) \to \pi^+\pi^-\Upsilon(1S)$ $(m = 1,2)$, are distinct signals for $\Upsilon(5S) \to \pi^+\pi^- h_b(1P)$ and $\pi^+\pi^- h_b(2P)$ with 5.5σ and 11.2σ significance, respectively, and a hint of $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1D)$. This is the first observation of the $h_b(1P)$ and $h_b(2P)$ bottomonium states. The prominent h_b signals – similar in strength to the $\Upsilon(nS)$ signals – are somewhat surprising because the $\Upsilon(5S) \to \pi^+\pi^- h_b$ process requires a b-quark spin-flip and is expected to be supressed.

4.2 $M(\pi^\pm h_b(mP))$ distributions

The huge number of events in the $h_b(1P)$ and $h_b(2P)$ signal peaks in Fig. 4 ($\simeq 50$ K and $\simeq 84$ K events, respectively) permitted an investigation of the resonant substructure in $\Upsilon(5S) \to \pi^+\pi^- h_b(mP)$ decays.[14] Figure 5(a) shows the $h_b(1P)$ yield determined from fits to the $\pi^+\pi^-$ recoil mass spectrum for different values of $\pi^\pm h_b(1P)$ mass, determined from $\pi^+\pi^-$ missing mass measurements of the h_b signals in bins of the mass recoiling

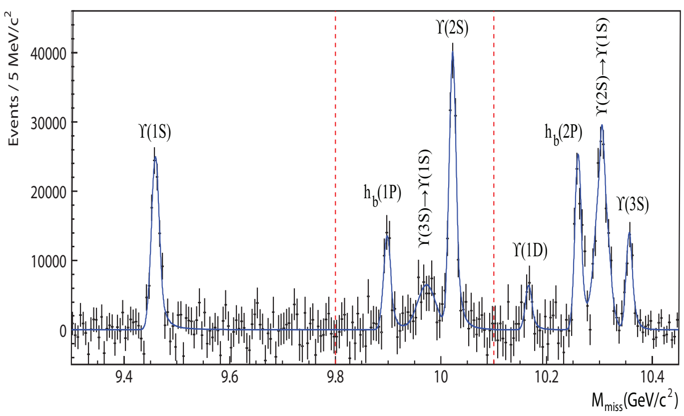

Figure 4: The background-subtracted recoil mass distribution with the signal component from the fit superimposed. The vertical lines indicate the boundaries used for the piecewise fit.

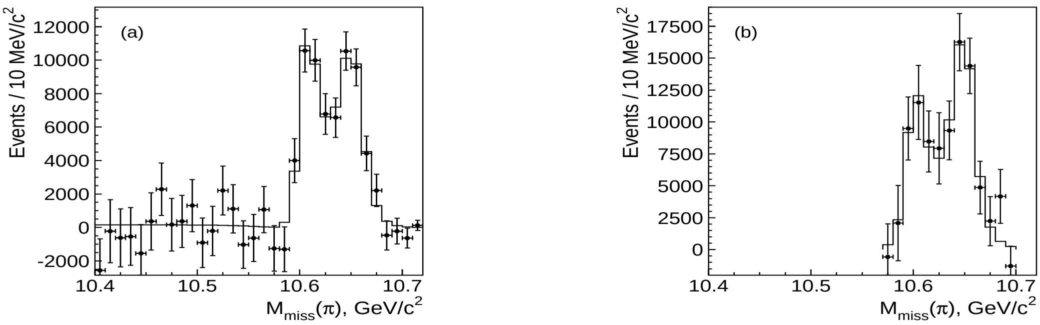

Figure 5: (a) $h_b(1P)$ and (b) $h_b(2P)$ yields *vs.* $M_{\rm miss}(\pi)$. The histograms are the fit results.

against one of the pions. Figure 5(b) shows the corresponding $\pi^{\pm}h_b(2P)$ mass distribution.

As is evident from the figures, the $h_b(1P)$ and $h_b(2P)$ signals are entirely due to two structures in $M(\pi^{\pm}h_b(mP))$, one with peak mass near 10610 MeV and the other with peak mass near 10650 MeV. In the following, these structures are referred to as the $Z_b(10610)$ and $Z_b(10650)$, respectively. The histograms in each figure show the results of fits to the mass spectra using two Breit Wigner (BW) amplitudes to represent the Z_b peaks plus a phase-space component. The fitted results for the BW parameters for the two Z_b peaks, which are consistent with being the same for both decay channels, are listed below in Table 1. For both spectra, the fitted strengths of the phase space term are consistent with being zero.

4.3 $M(\pi^{\pm}\Upsilon(nS))$ distributions in $\Upsilon(5S)\to\pi^+\pi^-\Upsilon(nS)$ decays

Belle also made an investigation of possible resonant substructure in fully reconstructed $\Upsilon(5S)\to\pi^+\pi^-\Upsilon(nS)$ decays ($n=1,2,3$) [14]. Figure 6 shows the $M^2(\Upsilon(2S)\pi)$ (vertical) *vs.* $M(\pi^+\pi^-)$ (horizontal) Dalitz plot for $\Upsilon(5S)\to\pi^+\pi^-\Upsilon(2S)$ decays. Here, to avoid double counting, only the highest mass $\Upsilon(2S)\pi$ combination is plotted. In the figure there is a sharp vertical band at small $\pi^+\pi^-$ masses caused by background from converted photons, and two distinct horizontal clusters near $M^2(\Upsilon(2S)\pi)=112.6$ GeV^2 and 113.3 GeV^2, near the locations expected for the $Z_b(10610)$ and $Z_b(10650)$. The $\pi^+\pi^-\Upsilon(1S)$ and $\pi^+\pi^-\Upsilon(3S)$ Dalitz plots show similar structures.

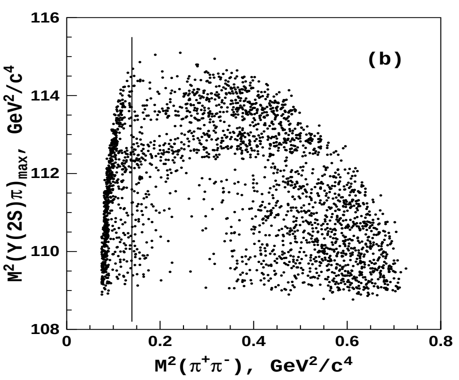

Figure 6: $M^2(\Upsilon(2S)\pi)$ *vs.* $M(\pi^+\pi^-)$ Dalitz plot for $\Upsilon(5S)\to\pi^+\pi^-\Upsilon(2S)$ decays.

The Dalitz plots are fitted with a model that includes BW amplitudes to represent the two Z_b states, terms that account for possible contributions in the $\pi^+\pi^-$ system from the $f_0(980)$ and $f_2(1270)$ resonances, and a non-resonant amplitude using a form suggested by Voloshin [58]. The regions of the Dalitz plots contaminated by photon conversion backgound (*i.e.* to the left of the vertical line in Fig. 6) are excluded from the fits. $M(\Upsilon(nS)\pi)$ and $M(\pi^+\pi^-)$ projections with the results of the fits superimposed are shown in Fig. 4.3 and included in Table 1. The $Z_b(10610)$ and $Z_b(10650)$ mass and width measurements from the five different channels agree within their errors.

The averages of the five mass and width measurements for the $Z_b(10610)$ are $M = 10607.2 \pm 2.0$ MeV and $\Gamma = 18.4 \pm 2.4$ MeV; for the $Z_b(10650)$, the averages are $M = 10652.2 \pm 1.5$ MeV and $\Gamma = 11.5 \pm 2.2$ MeV. These are very near the $m_B + M_{B^*} = 10604.3 \pm 0.6$ MeV and $2m_{B^*} = 10650.2 \pm 1.0$ MeV[47] mass thresholds, respectively, which is suggestive of virtual molecule-like structures [59], although other interpretations have been proposed [60].

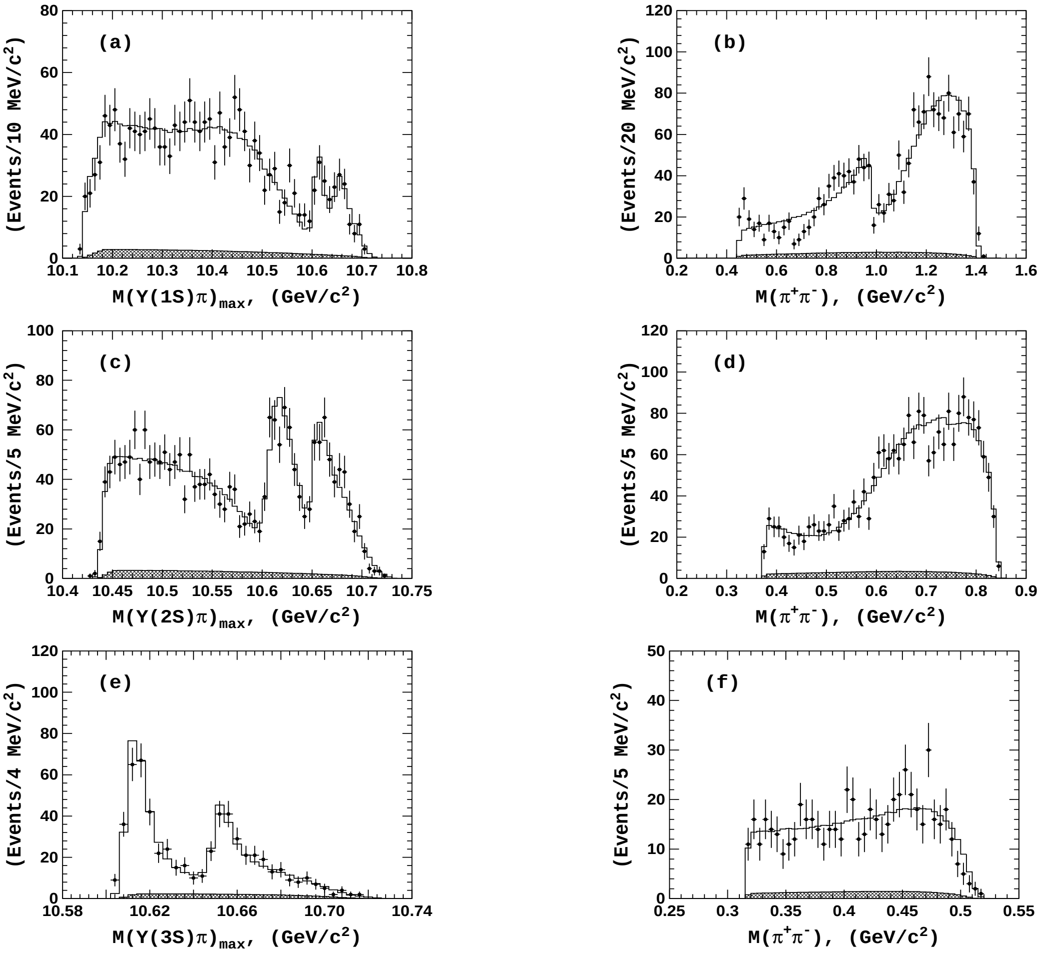

Figure 7: $M(\Upsilon(nS)\pi)$ and $M(\pi^+\pi^-)$ projections with fit results superimposed for the $\Upsilon(1S)$ (a,b), $\Upsilon(2S)$ (c,d) and $\Upsilon(3S)$ signals. The hatched histograms are sideband-determined backgrounds.

Table 1: Results for the $Z_b(10610)$ and $Z_b(10650)$ parameters obtained from $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1,2,3$) and $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ ($m = 1,2$) analyses.

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	13^{+10+9}_{-8-7}
$M[Z_b(10650)]$, MeV	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7^{+11}_{-7}$

4.4 The transitions $h_b(1P,2P) \to \gamma\eta_b(1S,2S)$ and the discovery of the $\eta_b(2S)$

In studies of bottomonium physics, the $\Upsilon(1S)$-$\eta_b(1S)$ mass difference has special importance since this determines the scale of the spin-spin hyperfine interaction term in the $B\bar{B}$ potential. This is accessible to Lattice QCD calculations, which give values that from $\Delta_{\rm hfs}(1S) = 47$ MeV to 59 MeV [61]. The $\eta_b(1S)$ was discovered by the BaBar collaboration in the $M1$ radiative process $\Upsilon(3S) \to \gamma\eta_b(1S)$ [34]. BaBar produced the first measurement of the splitting to be $\Delta_{\rm hfs}(1S) = 71.4 \pm 4.1$ MeV, which is outside the theoretical range. This measurement was an experimental *tour-de-force* because the $\Upsilon(3S) \to \gamma\eta_b$ environment is very difficult, with a weak signal and substantial backgrounds that make the extraction of a precise mass value difficult.

The Belle observation of strong signals for $h_b(1s)$ and $h_b(2S)$ in inclusive $\Upsilon(5S) \to \pi^+\pi^- X$ decays, provides another way to access the $\eta_b(1S)$, and that is via the $E1$ transitions, $h_b(1P,2P) \to \gamma\eta_b(1S)$. Figures 8(a) and (b) show the $h_b(1S)$ and $h_b(2P)$ signal yields determined from fitting the $\pi^+\pi^-$-recoil mass spectra, but this time in bins of $\pi^+\pi^-\gamma$ missing mass. In this measurement, γs that are not associated with a $\pi^0 \to \gamma\gamma$ decay are combined with the $\pi^+\pi^-$ pairs to determine $M_{\rm miss}(\pi^+\pi^-\gamma)$, which is plotted on the horizontal axis [62]. Distinct peaks near 9.4 GeV corresponding to the $\eta_b(1S)$ are evident in both distributions. These data are used to determine the hyperfine splitting $\Delta_{\rm hfs}(1S) = 57.9 \pm 2.3$ MeV and total width $\Gamma_{\eta_b(1S)} = 10.8 \pm 5.8$ MeV. This measurement of $\Delta_{\rm hfs}(1S)$ has improved precision and has a central value that is about 2.9σ higher than the BaBar measurement and within the range of theoretical expectations.

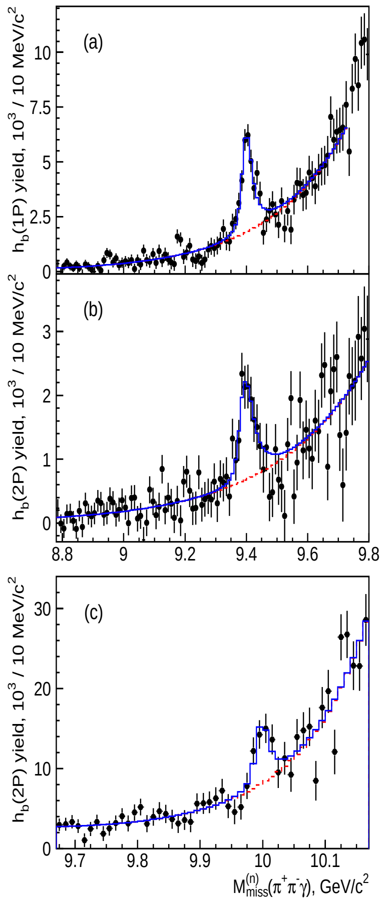

Figure 8: **a)** The $h_b(1P)$ yield *vs.* $M_{\rm miss}(\pi^+\pi^-\gamma)$ and **b)** the $h_b(2P)$ yield *vs.* $M_{\rm miss}(\pi^+\pi^-\gamma)$ inn the $\eta_b(1S)$ mass region. **c)** The $h_b(2P)$ yield *vs.* $M_{\rm miss}(\pi^+\pi^-\gamma)$ inn the $\eta_b(2S)$ mass region.

Figures 8(c) shows the $h_b(2P)$ signal yields determined from fitting the $\pi^+\pi^-$ recoil spectrum in $\pi^+\pi^-\gamma$ bins in the mass range expected for the $\eta_b(2S)$, where a prominent peak can be seen near 10 GeV. Belle identifies this as the first observation of the $\eta_b(2P)$ and measures $\Delta_{\rm hfs}(2S) = 24.3 \pm 4.3$ MeV.

As mentioned above, the LQCD calculations of $\Delta_{\rm hfs}(nS)$ produce a range of values that reflect the different approximations that are necessary for managable lattice calculations. On the other hand, in ratios of the splittings between different radial states, many of these uncertainties cancel. Thus, at least for the time being, measurements of these ratios present the strongest challenges for theory. The Belle measurement of the ratio $\Delta_{\rm hfs}(2S)/\Delta_{\rm hfs}(1S) = 0.42 \pm 0.08$ is in agreement with a LQCD prediction of 0.40 ± 0.06 [61].

5. Search for the H-dibaryon in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays.

As mentioned in the intoduction above, recent theoretical results motivate searches for the H with mass near the $M_H = 2m_\Lambda$ threshold. This mass region is especially interesting, because very general theoretical arguements ensure that for masses approaching the $2m_\Lambda$ threshold from below, the H would behave more and more like a $\Lambda\Lambda$ analog of the deuteron, and for masses approaching $2m_\Lambda$ from above, the H would look more and more like a virtual dineutron resonance, independently of its dynamical origin [63]. If its mass is below $2m_\Lambda$, the H would predominantly decay via $\Delta S = +1$ weak transitions to Λn, $\Sigma^- p$, $\Sigma^0 n$ or $\Lambda p\pi^-$ final states. If its mass is above $2m_\Lambda$, but below $m_{\Xi^0} + m_n$ $(= 2m_\Lambda + 23.1$ MeV), the H would decay via strong interactions to $\Lambda\Lambda$ 100% of the time.

Decays of narrow $\Upsilon(nS)$ $(n = 1,2,3)$ bottomonium $(b\bar{b})$ resonances are particularly well suited for searches for deuteron-like multiquark states with non-zero strangeness. The $\Upsilon(nS)$ states are flavor-$SU(3)$ singlets and primarily decay via the three-gluon annihilation process (*e.g.*, $(Bf(\Upsilon(1S) \to ggg) = 81.7 \pm 0.7\%$ [47]). The gluons materialize into $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ pairs in roughly equal numbers. The high density of quarks and antiquarks in the limited final-state phase space is conducive to the production of multi-quark systems, as demonstrated by large branching fractions for inclusive antideuteron $(\bar{d})$ production: $Bf(\Upsilon(1S) \to \bar{d}X) = (2.9 \pm 0.3) \times 10^{-5}$ and $Bf(\Upsilon(2S) \to \bar{d}X) = (3.4 \pm 0.6) \times 10^{-5}$ [64]. An upper limit for the production of a six-quark $S = -2$ state in $\Upsilon(nS)$ decays that is substantially below that for the six-quark antideuteron would be strong evidence against its existence.

Belle recently completed a search for H-dibaryon production in the inclusive decay chains $\Upsilon(1S,2S) \to HX$; $H \to \Lambda p\pi^-$ and $H \to \Lambda\Lambda$ [65], using data samples containing 102 million $\Upsilon(1S)$ and 158 million $\Upsilon(2S)$ decays. The search strategy assumed equal $\Upsilon(1S)$ and $\Upsilon(2S)$ branching fractions: *i.e.,* $Bf(\Upsilon(1S) \to HX) = Bf(\Upsilon(2S) \to HX) \equiv Bf(\Upsilon(1S,2S) \to HX)$.

The resulting continuum-subtracted $M(\Lambda p\pi^-)$ $(M(\bar{\Lambda}\bar{p}\pi^+))$ distribution for the combined $\Upsilon(1S)$ and $\Upsilon(2S)$ samples, shown in the top (bottom) left-hand panels of Fig. 9, has no evident $H \to \Lambda p\pi^-$ $(\bar{H} \to \bar{\Lambda}\bar{p}\pi^+)$ signal. The curve in the figure is the result of a fit using a threshold function to model the background; fit residuals are also shown. The dashed curves in the figures show the expected H signal for a $\Upsilon(1S,2S) \to HX$ branching fraction that is $1/20^{\rm th}$ that for antideuterons.

The panels on the right of Fig. 9 show the $M(\Lambda\Lambda)$ (above) and $M(\bar{\Lambda}\bar{\Lambda})$ (below) distributions for events that satisfy the selection requirements. Here there is no sign of a near-threshold enhancement similar to that reported by the E522 collaboration [25] nor any other evident signal for $H \to \Lambda\Lambda$ $(\bar{H} \to \bar{\Lambda}\bar{\Lambda})$. The curve is the result of a background-only fit using the functional form described above; fit residuals are also shown. Expectations for a signal branching fraction that is $1/20^{\rm th}$ that for the antideuterons is indicated with a dashed curve.

In the absence of any sign of an H-dibaryon in either the $\Lambda p\pi$ or the $\Lambda\Lambda$ mode, we set the 90% CL $(M_H - 2m_\Lambda)$-dependent branching fraction upper limits for the $\Lambda p\pi^-$ and $\Lambda\Lambda$ (for $\Gamma = 0$) mode shown in Figure 10. These limits are all more than an order of magnitude lower than the average of measured values of $Bf(\Upsilon(1,2S) \to \bar{d}X)$, shown in Fig. 10 as a horizontal dotted line.

These new Belle results are some of the most stringent constraints to date on the existence of an H-dibaryon with mass near the $2m_\Lambda$ threshold [66]. Since $\Upsilon \to$ hadrons decays produce final states that are flavor-$SU(3)$ symmetric, this suggests that if an H-dibaryon exists in this mass range,

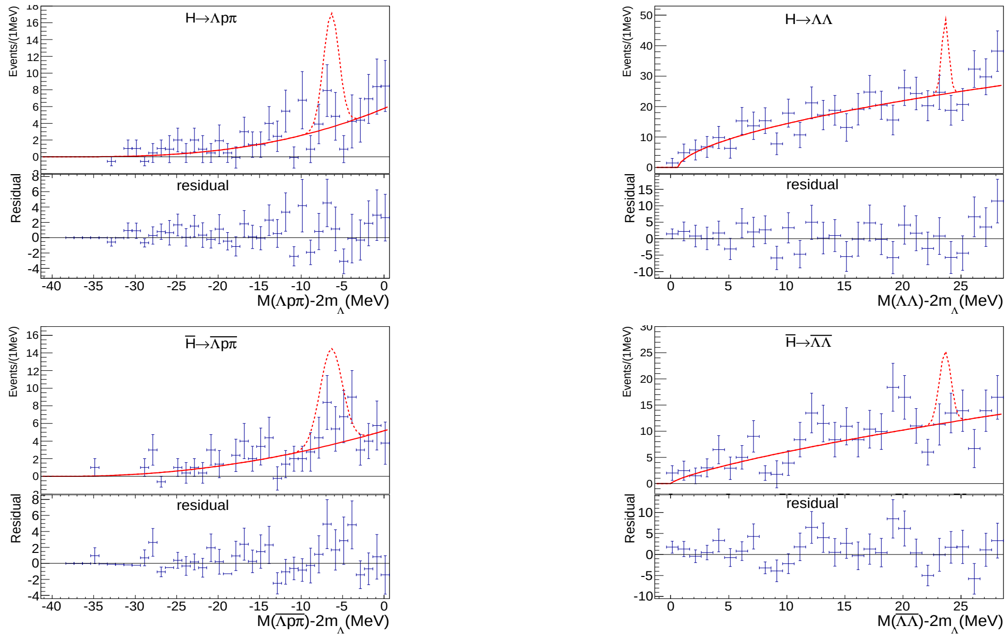

Figure 9: Top: The continuum-subtracted $M(\Lambda p\pi^-)$ (left) and $M(\Lambda\Lambda)$ (right) distributions with the residuals from a background-only fit shown below. Here the $\Upsilon(1S)$ and $\Upsilon(2S)$ data samples are combined. The curve shows the results of the background-only fit described in the text. The dashed curve shows the expected H signal for a $\Upsilon(1S,2S)\to HX$ branching fraction that is $1/20^{\rm th}$ that for antideuterons. **Bottom:** The corresponding $M(\bar{\Lambda}\bar{p}\pi^+)$ (left) and $M(\bar{\Lambda}\bar{\Lambda})$ distributions.

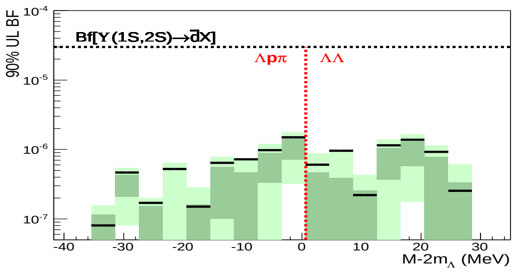

Figure 10: Upper limits (at 90% CL) for $Bf(\Upsilon(1S,2S)\to H\ X)\cdot Bf(H\to f_i)$ for a narrow ($\Gamma=0$) H-dibaryon *vs.* M_H-2m_Λ are shown as solid horizontal bars. The one (two) sigma bands are shown as the darker (lighter) bands. The vertical dotted line indicates the $M_H=2m_\Lambda$ threshold. The limits below (above) the $2m_\Lambda$ threshold are for $f_1=\Lambda p\pi^-$ ($f_2=\Lambda\Lambda$). The horizontal dotted line indicates the average PDG value for $Bf(\Upsilon(1S,2S)\to\bar{d}\,X)$.

it must have very different dynamical properties than the deuteron, or, in the case of $M_H<2m_\Lambda$, a strongly suppressed $H\to\Lambda p\pi^-$ decay mode.

6. Comments

After years of theoretical and experimental work, a large assortment of particles, the XYZ mesons, have been found that can not be accounted for by the standard mesons are quark-antiquark pairs rule that has been in common practice. There are now almost twenty candidates, a number that continues to grow rapidly. Many of these new mesons are close to particle-antiparticle thresholds and look very much like molecular structures of color-singlet mesons, however others are far from thresholds, which make molecular assignments less compelling. One feature of these states are their strong decays to hidden quarkonium states. In cases where partial width measurements have been possible, the results are usually much larger than those measured for conventional quarkonium states. Likewise, decays to open-flavor states seem to be suppressed compared to those for quarkonium mesons.

Few of the observed states were predicted in advance by theorists, while some predicted states, such as charged partners of the $X(3872)$ have been searched for but not been seen [42]. Moreover, none of the new particles make compelling matches to any of the states that are predicted by the QCD-motivated models that theorists seem to really like. The experimental limits on pentaquarks and the H-dibaryon keep getting more stringent with no compelling signs for either of them. Attempts have been made to attribute some of the XYZ states to diquark-diantiquark color bound states [67], however, these models predict that these structures should form flavor-$SU(3)$ multiplets and, so far at least, no multiplet partners of the observed states have been found.

This remains very much an experiment-dominated field of research. Hopefully as the list of XYZ states expands and the properties of the established states are better know, some pattern will emerge that will allow someone to make sense of it all.

7. Acknowledgements

I thank the organizers of this meeting for inviting me to present these results. In addition I compliment them on their well organized and interesting meeting. This work is supported by the Korean national Research Foundation via Grant No. 2011-0029457 and WCU Grant No. R32-10155.

References

[1] M. Gell-Mann, Phys. Lett. **8**, 214 (1964).

[2] G. Zweig, CERN Report 8419/Th.401 (1964).

[3] D. Strottman, Phys. Rev. D **20**, 748 (1979).

[4] D. Diakonov, V. Petrov and M. Polyakov, Z. Phys. A **359**, 305 (1997).

[5] R.L. Jaffe, Phys. Rev. Lett. **38**, 195 (1977).

[6] W.-M. Yao, *et al.* (Particle Data Group), J. Phys. G: Nucl. Part. Phys. **33** 1, (2006). See, in particular "Pentaquark Update" by G. Trilling on page 1019; see also the review by R. A. Schunacher, arXiv:nucl-ex/051204.

[7] V. Dorofeev (VES Collaboration) hep-ex/9905002 and G.S. Abrams *et al.* (E852 Collaboration), Phys. Rev. Lett. **81**, 5760 (1998).

[8] See, for example, T. Barnes, arXiv:hep-ph/0007296.

[9] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).

[10] B. Aubert *et al.* (Babar Collaboration), Phys. Rev. Lett. **95**, 142001 (2005).

[11] S. Godfrey and S.L. Olsen Annu. Rev. Nucl. Part. Sci. **58**, 51 (2008).

[12] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 142001 (2008).

[13] R. Mizuk *et al.* (Belle Collaboration), Phys. Rev. D **78**, 072004 (2008).

[14] A. Bondar *et al.* (Belle Collaboration), Phys. Rev. Lett. **108**, 122001 (2012).

[15] M. Ablikim *et al.* (BESIII Collaboration), arXiv:1303.5949 [hep-ex], submitted for publication in Physical Review Letters, and Z.Q. Liu *et al.* (Belle Collaboration), arXiv:1304.0121 [hep-ex], submitted for publication in Physical Review Letters.

[16] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985).

[17] S. Uehara *et al.* (Belle Collaboration), Phys. Rev. Lett. **96**, 082003 (2006).

[18] M. Danysz, K. Garbowska, J. Pniewski and J. Zakrzewski, Phys. Rev. Lett. **11**, 29 (1963); D.J. Prowse, Phys. Rev. Lett. **17**, 782 (1966); S. Aoki, *et al.* Prog. Theor. Phys. **85**, 1287 (1991).

[19] H. Takahashi *et al.*, Phys. Rev. Lett. **87**, 212502 (2001).

[20] K. Nakazawa *et al.* (E176 Collaboration), Nucl. Phys. A **835**, 207 (2010).

[21] S.R. Beane *et al.* (NPLQCD Collaboration), Phys. Rev. Lett. **106**, 162001 (2011).

[22] S.R. Beane *et al.* (NPLQCD Collaboration), Mod. Phys. Lett. A **26**, 2587 (2011).

[23] T. Inoue *et al.* (HALQCD Collaboration), Phys. Rev. Lett. **106**, 162002 (2011).

[24] S.R. Carames and A. Valcarce, Rhys. Rev. C **85**, 045202 (2012).

[25] C.J. Yoon *et al.* (KEK-PS E522 Collaboration), Phys. Rev. C **75**, 022201(R) (2007). See also J.K. Ahn *et al.* (KEK-PS E224 Collaboration), Phys. Lett. **B444**, 267 (1998) and J. Belz *et al.* (BNL E888 Collaboration), Phys. Rev. D **53**, 3487 (1996).

[26] R.W. Stotzer *et al.* (BNL-E836 Collaboration), Phys. Rev. Lett. **78**, 3646 (1997).

[27] A. Alavi-Harati *et al.* (KTeV Collaboration), Phys. Rev. Lett. **84**, 2593 (2003).

[28] I. Chemakin *et al.* (E910 Collaboration), Nucl. Phys. A **639**, 407c (1998).

[29] J.K. Ahn *et al.* (KEK-PS E224 Collaboration), Phys. Lett. B **444**, 267 (1998); J. Belz *et al.*, Phys. Rev. Lett. **76**, 3277 (1996) & Phys. Rev. C **56**, 1164 (1997).

[30] V. Bhardwaj *et al.* (Belle Collaboration), arXiv:1304.3975 [hep-ex], submitted for publication in Physical Review Letters.

[31] I. Adachi *et al.* (Belle Collaboration), Phys. Rev. Lett. **108**, 032001 (2012).

[32] R. Mizuk *et al.* (Belle Collaboration), Phys. Rev. Lett. **109**, 232002 (2012).

[33] G. Bonvicini *et al.* (CLEO Collaboration), Phys. Rev. D **70**, 032001 (2004), P. del Amo Sanchez *et al.* (Babar Collaboration), Phys. Rev. D **82**, 111102 (2010) and G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. Lett. **108**, 152001 (2012).

[34] B. Aubert *et al.* (Babar Collaboration), Phys. Rev. Lett. **101**, 071801 (2008).

[35] In this report the inclusion of charge-conjugate states is always implied.

[36] K. Abe *et al.* (Belle Collaboration), arXiv:hep-ex/0505037.

[37] B. Aubert *et al.* (Babar Collaboration), Phys. Rev. Lett. **102**, 132901 (2009).

[38] V. Bhardwaj *et al.* (Belle Collaboration), Phys. Rev. Lett. **107**, 091803 (2011).

PoS(Bormio 2013)004

[39] P. del Amo Sanchez *et al.* (Babar Collaboration), Phys. Rev. D **82**, 011101 (2010).

[40] G. Gokrhoo *et al.* (Belle Collaboration), Phys. Rev. Lett. **97**, 162002 (2006), T. Ashev *et al.* (Belle Collaboration), Phys. Rev. D **81**, 031103(R) (2010) and B. Aubert *et al.* (Babar Collaboration), Phys. Rev. D **77**, 011102 (2008).

[41] K. Abe *et al.* (Belle Collaboration), arXiv:hep-ex/0505038 and A. Abulencia, *et al.* (CDF Collaboration), Phys. Rev. Lett. **96**, 102002 (2006).

[42] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. D **84**, 052004 (2011).

[43] A. Abulencia, *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, 132002 (2007).

[44] R. Aaij *et al.* (LHCb Collaboration), arXiv:1302.6269 [hep-ex], submitted to Physical Review Letters.

[45] In the bottomonium system $(m(\chi'_{b2}) - m(\chi'_{b1}))/(m(\chi_{b2}) - m(\chi_{b1})) = 0.68 \pm 0.02$.

[46] T. Barnes, S. Godfrey and E. S. Swanson, Phys. Rev. D **72** 054026 (2005).

[47] J. Beringer *et al.* (Particle Data Group) Phys. Rev. D **86** 010001 (2012).

[48] See, for example, M.B. Voloshin and L.B. Okun, JETP Lett. **23**, 333 (1976); M. Bander, G.L. Shaw and P. Thomas, Phys. Rev. Lett. **36**, 695 (1976); A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. Lett. **38**, 317 (1977); A.V. Manohar and M.B. Wise, Nucl. Phys. B **339**, 17 (1993); N.A. Törnqvist, hep-ph/0308277; F.E. Close and P.R. Page, Phys. Lett. B **578**, 119 (2003); C.-Y. Wong, Phys. Rev. C **69**, 055202 (2004); S. Pakvasa and M. Suzuki, Phys. Lett. B **579**, 67 (2004); E. Braaten and M. Kusunoki, Phys. Rev. D **69**, 114012 (2004); E.S. Swanson, Phys. Lett. B **588**, 189 (2004); D. Gamermann and E. Oset, Phys. Rev. D **80**, 014003 (2009), & Phys. Rev. D **81**, 014029 (2010).

[49] Q. He *et al.* (CLEO Collaboration), Phys. Rev. D **74**, 091104(R) (2006) and C. Z. Yuan *et al.* (Belle Collaboration), Phys. Rev. Lett. **99** 182004 (2008).

[50] J. Z. Bai *et al.* (BES II Collaboration), Phys. Rev. Lett. **88**, 101802 (2002).

[51] X. H. Mo *et al.* Phys. Lett. **B640**, 182 (2006).

[52] G. Pakhlova *et al.* (Belle Collaboration), Phys. Rev. D **83** 011101(R) (2011), Phys. Rev. Lett. **101**, 172001 (2008), Phys. Rev. D **80**, 091101 (2009), Phys. Rev. Lett. **100**, 062001 (2008), Phys. Rev. Lett. **98**, 092001 (2007) and Phys. Rev. D **77**, 011103 (2008).

[53] B. Aubert *et al.* (Babar Collaboration), Phys. Rev. Lett. **98**, 212001 (2007).

[54] X. L. Wang *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 142002 (2008).

[55] W. S. Hou, Phys. Rev. D **74**, 017504 (2006).

[56] K. F. Chen *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 112001 (2008).

[57] K. F. Chen *et al.* (Belle Collaboration), Phys. Rev. D **82**, 091106(R) (2010).

[58] M.B. Voloshin, Phys. Rev. D **74**, 054022 (2006).

[59] A.E. Bondar *et al.*, Phys. Rev. D **84**, 054010 (2011),

[60] D.V. Bugg, Europhys. Lett. **96**, 11002 (2011), I.V. Danilkin, V.D. Orlovsky and Yu.A. Simonov, Phys. Rev. D **85**, 034012 (2012), C.-Y. Cui, Y.-L. Liu and M.-Q. Huang, Phys. Rev. D **85**, 054014 (2012), and T. Guo, L. Cao, M.-Z. Zhou and H. Chen, arXiv:1106.2284 [hep-ph].

[61] S. Meinel, Phys. Rev. D **82**, 114502 (2010).

[62] R. Mizuk *et al.* (Belle Collaboration), Phys. Rev. Lett. **109**, 232002 (2012).

[63] E. Braaten, private communication. See also, E. Braaten and H.-W. Hammer, Phys. Rept. **428**, 259 (2006).

[64] D.M. Asner *et al.* (CLEO Collaboration), Phys. Rev. D **75**, 012009 (2007), see also H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **236**, 102 (1990).

[65] B.H. Kim *et al.* (Belle Collaboration), arXiv:1302.4028 [hep-ex], submitted for publication in Physical Review Letters.

[66] The sample of $\Lambda\Lambda$ plus $\overline{\Lambda}\overline{\Lambda}$ events with $M(\Lambda\Lambda)$ below the $m_{\Xi^-}+m_p$ threshold detected in the Belle experiment, as determined from the fits to the two dimensional $M(p_1\pi_1^-)$ *vs.* $M(p_2\pi_2^-)$ histograms, contains 2.3×10^3 events and is nearly two orders of magnitude larger than the 28 $\Lambda\Lambda$ events with invariant mass below $m_{\Xi^-}+m_p$ used in KEK experiment E522.

[67] L. Maiani *et al.*, Phys. Rev. D **71**, 014028 (2005) and references cited therein.