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Spectroscopy Update

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We review the status of spectroscopy, concentrating on the recent results in heavy quarkonia. We start from low excitations and move to the open flavor thresholds and beyond. We try to stress similarity between the observed phenomena in $b\bar{b}$, $c\bar{c}$ and even $s\bar{s}$ sectors. The main question to address is whether we have solid evidence for the exotic (non $q\bar{q}$) structure of mesons. We finish our update with mentioning recent results on baryons.

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Hadron spectroscopy provides a unique laboratory to study strong interactions at low energy. It is expected that QCD simulations on a lattice will provide an ultimate theory for spectroscopy, able to calculate hadron masses and decay properties from the first principles. Though the progress in Lattice QCD is rapid, its predictive power in many areas is still insufficient. Therefore effective theories and phenomenological models are widely used.

In the Quark Model the multibody dynamics of a relativistic system is ignored and hadrons are considered as bound states of constituent quarks. Mesons are $q\bar{q}$ pairs and baryons are qqq combinations. Other effective degrees of freedom, like constituent diquarks qq or valence gluons g, have been searched for in light hadron spectroscopy, however, no tetraquarks ($qq\overline{qq}$), hybrid mesons ($q\bar{q}g$) or glueballs (gg) have been established.

Application of the Quark Model to the heavy quarkonia was especially successful as the system is approximately nonrelativistic. Rather unexpectedly, highly excited charmonia and bottomonia showed numerous departures from predictions of the Quark Model. Since 2003 about a dozen of states was observed that do not fit the $q\bar{q}$ table. There is no general theoretical explanation for these observations.

We review the status of spectroscopy, concentrating on the recent results in heavy quarkonia. We start from low excitations and move to the open flavor thresholds and beyond. We consider the $b\bar{b}$, $c\bar{c}$ and in some cases $s\bar{s}$ states in parallel and try to stress similarity between the observed phenomena in different quarkonium sectors. We finish our update with mentioning recent results on baryons.

1. Heavy quarkonia below open flavor thresholds

1.1 $h_b(nP)$ and $\eta_b(mS)$

Spin-singlet states provide information on the spin-spin interaction between quark and antiquark. Observed in 2008, $\eta_b(1S)$ remained until recently the only known bottomonium spin-singlet state [1]. Inspired by earlier observation of the $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ transitions with high rates [2] and by observation of the $e^+e^- \to h_c\pi^+\pi^-$ process above $D\bar{D}$ threshold [3], Belle observed the $h_b(1P)$ and $h_b(2P)$ states using the transitions $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ [4]. Belle investigated the missing mass spectrum of the $\pi^+\pi^-$ pairs (see Fig. 1). The P-wave hyperfine splittings $\Delta M_{HF}(nP) = \sum_{J=0}^{2} \frac{2J+1}{9} m_{\chi_{bJ}(nP)} - m_{h_b(nP)}$ were measured to be $(+0.8\pm1.1)\,\mathrm{MeV}/c^2$ for $n=1$ and $(+0.5\pm1.2)\,\mathrm{MeV}/c^2$ for $n=2$ [5]. The numbers are consistent with zero, and this is in agreement with theoretical expectations [6]. In charmonium sector the measured $1P$ hyperfine splitting of $(-0.11\pm0.17)\,\mathrm{MeV}/c^2$ [7] is also consistent with zero with even higher accuracy.

Production of the $h_b(nP)$ involves spin-flip of heavy quark and should be suppressed as $(\frac{\Lambda_{QCD}}{m_b})^2$ relative to the $\Upsilon(nS)$. Experimentally no strong suppression was observed, implying contribution of an exotic mechanism (see section 2.2).

The electric-dipole transitions $h_b(nP) \to \eta_b(mS)\gamma$ are expected to be prominent [8]. To search for these transitions Belle measured the $h_b(nP)$ yield as a function of the $\pi^+\pi^-\gamma$ missing mass [5]. The $h_b(1P) \to \eta_b(1S)\gamma$ and $h_b(2P) \to \eta_b(1S)\gamma$ transitions were observed with significances of $15\,\sigma$ and $9\,\sigma$, respectively [see Fig. 2 (a) and (b)]. The $\eta_b(1S)$ signal is more clear than in previous measurements that used the $\Upsilon(2S,3S) \to h_b(nP)\gamma$ decays. The mass and width of the $\eta_b(1S)$ were

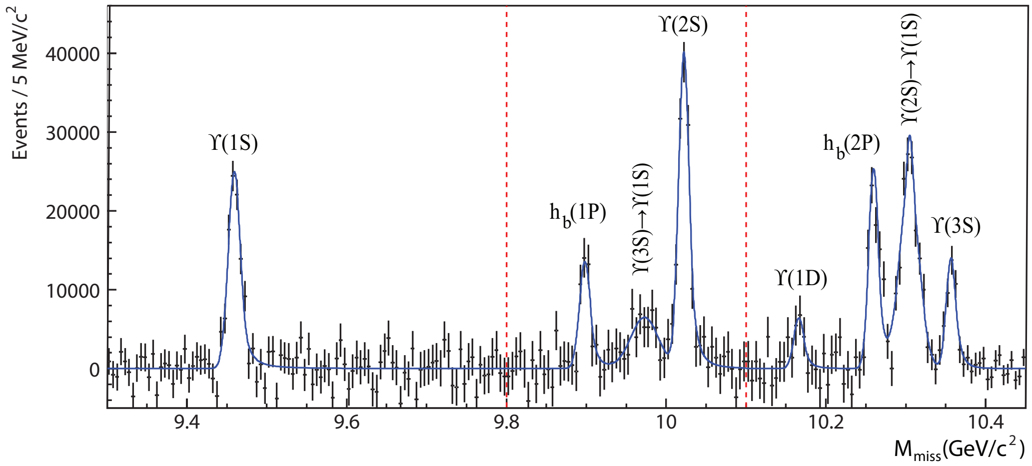

Figure 1: The inclusive $M_{\rm miss}(\pi^+\pi^-)$ spectrum with the combinatoric background and K^0_S contribution subtracted (points with errors) and signal component of the fit function overlaid (smooth curve). The vertical lines indicate boundaries of the fit regions.

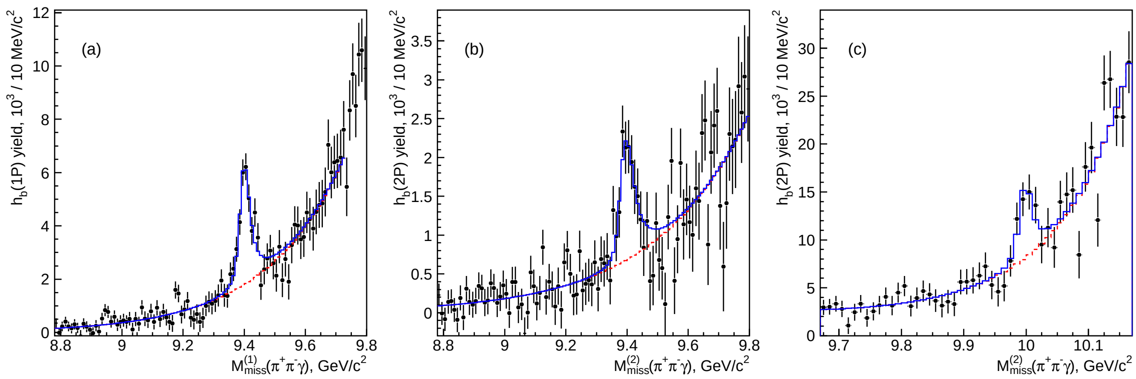

Figure 2: The $h_b(1P)$ (a) and $h_b(2P)$ (b)-(c) yields as a function of the $\pi^+\pi^-\gamma$ missing mass.

measured to be $m_{\eta_b(1S)} = (9402.4 \pm 1.5 \pm 1.8)\,{\rm MeV}/c^2$ and $\Gamma_{\eta_b(1S)} = (10.8^{+4.0}_{-3.7}{}^{+4.5}_{-2.0})\,{\rm MeV}$. The $\Gamma_{\eta_b(1S)}$ is a first measurement; the $m_{\eta_b(1S)}$ measurement is more precise than the current world average and is $(11.4 \pm 3.6)\,{\rm MeV}/c^2$ above the central value [7]. The hyperfine splitting, $\Delta M_{\rm HF}(1S) = (57.9 \pm 2.3)\,{\rm MeV}/c^2$, is in agreement with perturbative NRQCD $(41 \pm 14)\,{\rm MeV}/c^2$ [9] and Lattice $(60 \pm 8)\,{\rm MeV}/c^2$ [10] calculations.

Belle found first evidence for the $\eta_b(2S)$ using the $h_b(2P) \to \eta_b(2S)\gamma$ transition [see Fig. 2 (c)]. The $\eta_b(2S)$ significance is $4.4\,\sigma$ including systematic uncertainties and "look elsewhere" effect. The mass of the $\eta_b(2S)$ was measured to be $m_{\eta_b(2S)} = (9999.0 \pm 3.5\,^{+2.8}_{-1.9})\,{\rm MeV}/c^2$, the hyperfine splitting is $\Delta M_{\rm HF}(2S) = (24.3^{+4.0}_{-4.5})\,{\rm MeV}/c^2$. For the ratio of hyperfine splittings the theoretical uncertainties usually cancel. Belle measurement $\Delta M_{\rm HF}(2S)/\Delta M_{\rm HF}(1S) = 0.420^{+0.071}_{-0.079}$ is in agreement with theoretical calculations [9, 10, 11].

Belle measured also branching fractions $\mathscr{B}[h_b(1P) \to \eta_b(1S)\gamma] = (49.2 \pm 5.7\,^{+5.6}_{-3.3})\%$, $\mathscr{B}[h_b(2P) \to \eta_b(1S)\gamma] = (22.3 \pm 3.8\,^{+3.1}_{-3.3})\%$ and $\mathscr{B}[h_b(2P) \to \eta_b(2S)\gamma] = (47.5 \pm 10.5\,^{+6.8}_{-7.7})\%$. These branching fractions are somewhat higher than the quark model predictions [8].

1.2 $\chi_{bJ}(3P)$ states

Though the S-wave spin-triplet states $\Upsilon(nS)$ are known up to the fifth radial excitation ($n = 6$) from e^+e^- energy scans, the P-wave spin-triplet states $\chi_{bJ}(nP)$ were known until recently for $n = 1$ and $n = 2$ only. The $n = 3$ is expected to be the last excitation still below the $B\bar{B}$ threshold.

The ATLAS Collaboration observed the $\chi_{bJ}(3P)$ states produced inclusively in the pp collisions and reconstructed in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ channels, with $\Upsilon(1S,2S) \to \mu^+\mu^-$ [12]. The photon was reconstructed either through conversion to e^+e^- or by direct calorimetric measurement. The $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ spectra (see Fig. 3 top row) show the $\chi_{bJ}(3P)$ signals with

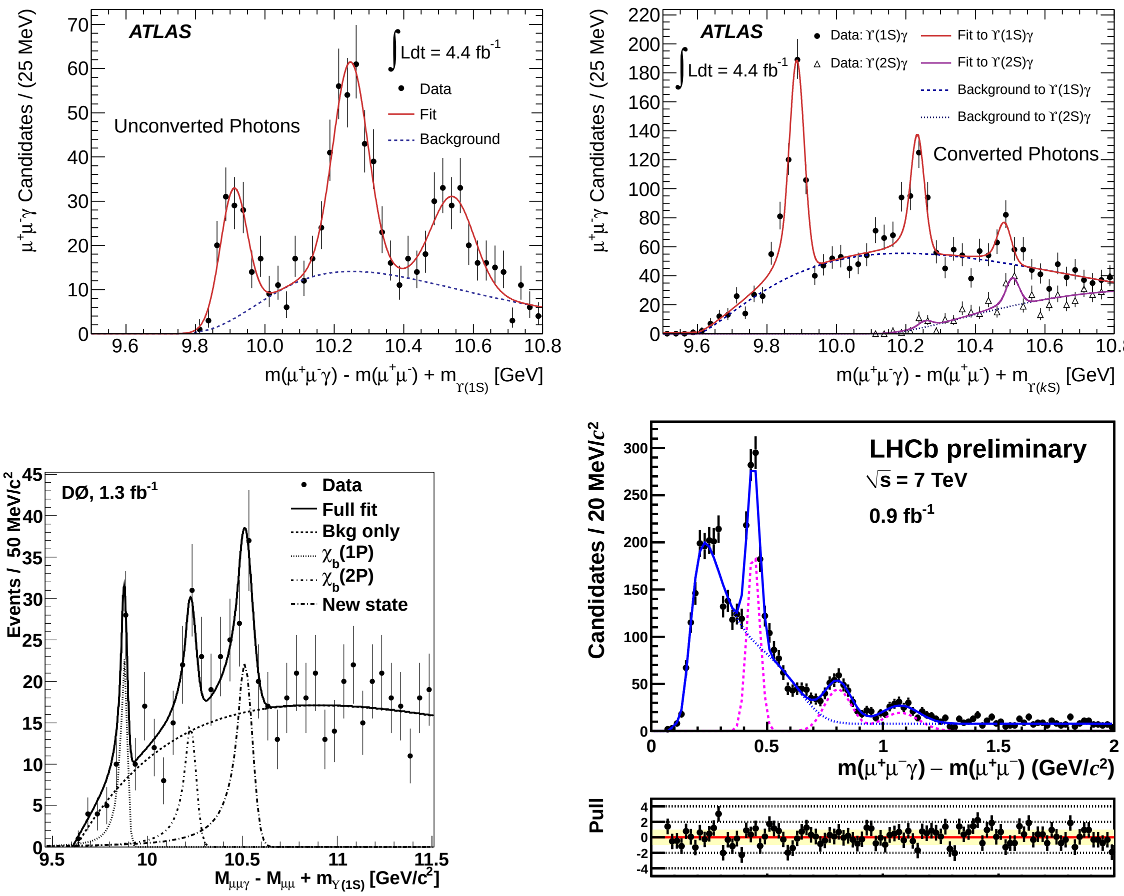

Figure 3: The $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ spectra with signals of $\chi_b(1P)$, $\chi_b(2P)$ and $\chi_b(3P)$ measured by ATLAS using unconverted photons (top left) and converted photons (top right), by D0 (bottom left) and by LHCb (bottom right).

significances exceeding $6\,\sigma$ for both photon reconstruction channels. Other peaks correspond to the signals of the known $\chi_{bJ}(1P,2P) \to \Upsilon(1S)\gamma$ transitions.

The mass resolution does not allow to discern individual $\chi_{bJ}(3P)$ states with $J = 0$, 1 and 2. Contribution of the $\chi_{b0}(3P)$ is expected to be small and is neglected. The splitting between $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ is fixed to the theoretical prediction of $12\,\mathrm{MeV}/c^2$ and the average mass is measured assuming equal normalization of the peaks. According to theoretical expectations, this mass is typically $1\,\mathrm{MeV}/c^2$ higher then $(2J+1)$-averaged mass of the $\chi_{bJ}(3P)$ triplet. The value measured with converted photons $(10530 \pm 5 \pm 9)\,\mathrm{MeV}/c^2$ has much higher accuracy compared to the calorimetric measurement $(10541 \pm 11 \pm 30)\,\mathrm{MeV}/c^2$ and is considered as a final result. It is in agreement with Quark Model expectations of typically $10525\,\mathrm{MeV}/c^2$ [13, 14].

The *D*0 and *LHCb* Collaborations confirmed the observation of the $\chi_b(3P)$ in the $\chi_b(3P) \to \Upsilon(1S)\gamma$ channel (see Fig. 3 bottom row). *D*0 used converted photons [15], while in the preliminary analysis LHCb used photons reconstructed in the electromagnetic calorimeter [16]. The results of D0 $(10551 \pm 14 \pm 17)\,\mathrm{MeV}/c^2$ and LHCb $(10535 \pm 10)\,\mathrm{MeV}/c^2$ are in agreement with ATLAS.

1.3 Evidence for $\psi_2(1D)$

Potential models predict that *D*-wave charmonium levels lie between the $D\bar{D}$ and $D\bar{D}^*$ thresholds [17]. The states η_{c2} with $J^{PC} = 2^{-+}$ and ψ_2 with $J^{PC} = 2^{--}$ can not decay to $D\bar{D}$ because of unnatural spin-parity, being the only undiscovered narrow charmonium levels.

Belle reported preliminary results on the resonant structure of the $B^+ \to K^+\chi_{c1}\gamma$ decays, with χ_{c1} reconstructed in the $J/\psi\gamma$ channel. Belle found the first evidence for the $\psi_2(1D)$ [see the $M(\chi_{c1}\gamma)$ spectrum in Fig. 4] with the mass of $M = 3823.5 \pm 2.8\,\mathrm{MeV}/c^2$ and the significance of

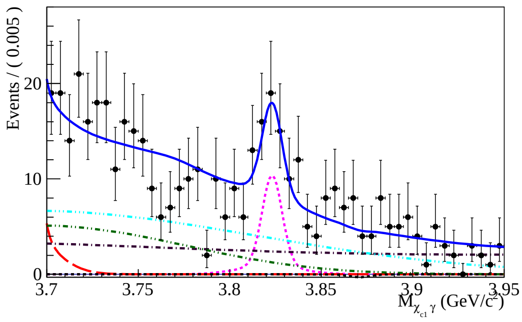

Figure 4: The $M(\chi_{c1}\gamma)$ spectrum for the $B^+ \to K^+\chi_{c1}\gamma$ decays.

$4.2\,\sigma$ including systematic uncertainty. Measured width is consistent with zero, $\Gamma = 4 \pm 6\,\mathrm{MeV}$; it is likely that the width is very small, since the state is observed in the radiative decay and the typical charmonium radiative decay widths are at the $O(100)\,\mathrm{keV}$ level. The odd *C*-parity (fixed by decay products) allows to discriminate between the η_{c2} and ψ_2 hypotheses. No signal is found in the $\chi_{c2}\gamma$ channel, in agreement with expectations for the ψ_2 [17].

Belle measured $\mathscr{B}[B^+ \to K^+\psi_2] \times \mathscr{B}[\psi_2 \to \chi_{c1}\gamma] = (9.7^{+2.8+1.1}_{-2.5-1.0}) \times 10^{-6}$. Given expected $\mathscr{B}[\psi_2 \to \chi_{c1}\gamma] \sim \frac{2}{3}$ [17], the $\mathscr{B}[B^+ \to K^+\psi_2]$ is a factor 50 smaller than corresponding branching fractions for the J/ψ, $\psi(2S)$ and χ_{c1} due to the factorization suppression [18].

2. Heavy quarkonia at open flavor thresholds

2.1 Status and recent results on $X(3872)$

$X(3872)$ is a state very close to the $D^0\bar{D}^{*0}$ threshold, $m_{X(3872)} - m_{D^{*0}} - m_{D^0} = -0.16 \pm 0.32\,\mathrm{MeV}/c^2$ [7]. The decays $X(3872) \to J/\psi\rho$ and $X(3872) \to J/\psi\omega$ have similar branching fractions, $\mathscr{B}_\omega/\mathscr{B}_\rho = 0.8 \pm 0.3$ [19, 20]; this corresponds to a strong violation of isospin symmetry. Favorite interpretation is a mixture of the charmonium state $\chi_{c1}(2P)$ and an *S*-wave $D^0\bar{D}^{*0}$

molecule [21], with molecular component responsible for the isospin violation and charmonium component accounting for the production in B meson decays and in high-energy $p\bar{p}$ and pp collisions. This interpretation is valid only for the spin-parity $J^{PC} = 1^{++}$, while experimentally 1^{++} is favored, but 2^{-+} is not excluded [22]. Discrimination between $J^P = 1^+$ and $J^P = 2^-$ via angular analysis will probably be within the reach of the LHCb. The radiative $X(3872) \to J/\psi\gamma$ decay is established, while there is an experimental controversy regarding the $X(3872) \to \psi(2S)\gamma$ [19, 23]. The dominant decay mode of the $X(3872)$ is $D^0\bar{D}^{*0}$ [24], as expected for the molecule, however, absolute branching fraction is not yet determined. These questions can be addressed at the next generation B-factory.

Recently Belle searched for the $X(3872)$ partner with opposite C-parity in $J/\psi\eta$ and $\chi_{c1}\gamma$ final states using B decays. Some molecular and tetraquark models predict such partners [25]. According to Belle preliminary results, no signals were found.

2.2 Observation of $Z_b(10610)$ and $Z_b(10650)$

Belle studied resonant structure of the $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ and $h_b(mP)\pi^+\pi^-$ decays ($n = 1,2,3$; $m = 1,2$) [26]. The $\Upsilon(nS)$ [$h_b(mP)$] states were reconstructed in the $\mu^+\mu^-$ channel [inclusively using missing mass of the $\pi^+\pi^-$ pairs]. Invariant mass spectra of the $\Upsilon(nS)\pi^\pm$ and $h_b(mP)\pi^\pm$ combinations are shown in Fig. 5. Each distribution shows two peaks. For the channels

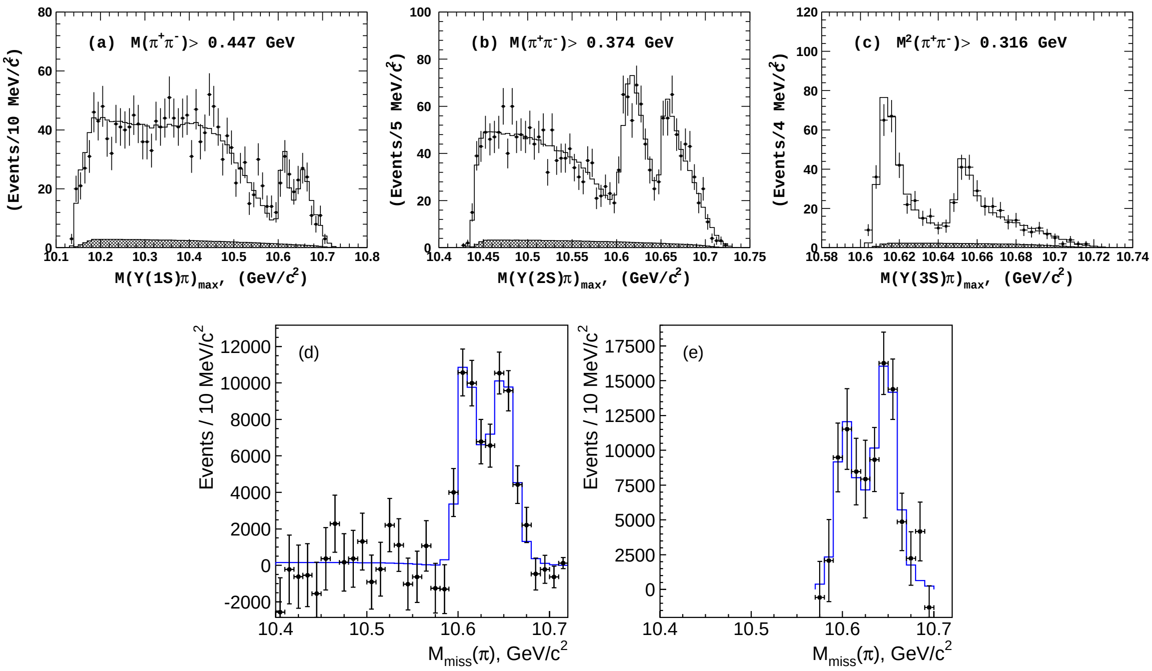

Figure 5: Invariant mass spectra of the (a) $\Upsilon(1S)\pi^\pm$, (b) $\Upsilon(2S)\pi^\pm$, (c) $\Upsilon(3S)\pi^\pm$, (d) $h_b(1P)\pi^\pm$ and (e) $h_b(2P)\pi^\pm$ combinations.

$\Upsilon(nS)\pi^+\pi^-$ [$h_b(mP)\pi^+\pi^-$] the Dalitz plot analyses [fits to one-dimensional distributions] were performed. The non-resonant contributions in the $h_b(mP)\pi^+\pi^-$ channels are negligible, justifying the one-dimensional analysis. Preliminary results of the angular analysis indicate that both states have the same spin-parity $J^P = 1^+$ [27], therefore coherent sum of Breit-Wigner amplitude was used to describe the signals. The masses and widths of the two peaks were found to be in good agreement among different channels (see Fig. 6). Averaged over the five decay channels parame-

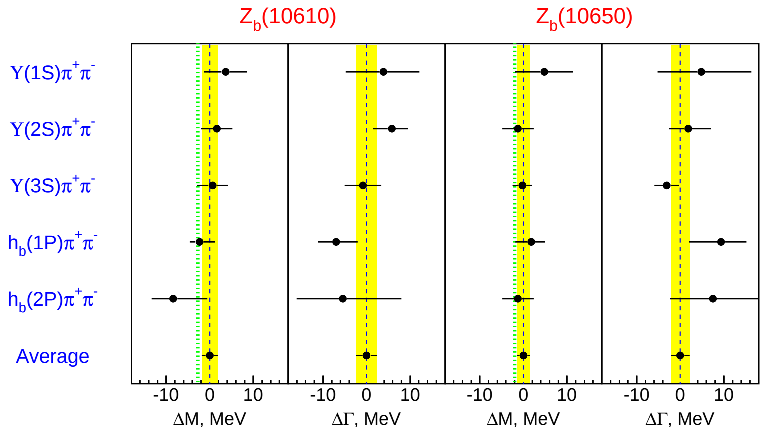

Figure 6: The deviations of the mass and width measurements of the $Z_b(10610)$ and $Z_b(10650)$ in different channels from the averaged over all channels value.

ters are $M_1 = (10607.4 \pm 2.0)\,\mathrm{MeV}/c^2$, $\Gamma_1 = (18.4 \pm 2.4)\,\mathrm{MeV}$ and $M_2 = (10652.2 \pm 1.5)\,\mathrm{MeV}/c^2$, $\Gamma_2 = (11.5 \pm 2.2)\,\mathrm{MeV}$. The peaks are identified as signals of two new states, named $Z_b(10610)$ and $Z_b(10650)$. Their quark content is exotic, for the Z_b^+ it is $|b\bar{b}u\bar{d}>$.

The masses of the $Z_b(10610)$ and $Z_b(10650)$ states are close to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, respectively, suggesting molecular interpretation. Under this assumption, all their properties are naturally explained in a model independent way [28], i.e. considering the heavy-quark spin structure only and not the binding mechanism. The Z_b contains a mixture of the ortho- and para-bottomonium with equal weights [therefore the decay to the $h_b(nP)$ is not suppressed compared to the $\Upsilon(nS)$] but with different signs between the components [this predicted different sign between the $h_b(nP)\pi$ and $\Upsilon(nS)\pi$ decay amplitudes, which was observed experimentally].

Given (i) molecular structure, (ii) proximity to the thresholds and (iii) finite widths $\Gamma_{Z_b} \sim 15\,\mathrm{MeV}$, it is natural to expect that the rates of the "fall-apart" decays $Z_b(10610) \to B\bar{B}^*$ and $Z_b(10650) \to B^*\bar{B}^*$ are substantial. To search for them Belle studied the $\Upsilon(5S) \to [B^{(*)}\bar{B}^*]^{\pm}\pi^{\mp}$ decays [29]. One B meson candidate was reconstructed fully using the $D^{(*)}\pi^+$ and $J/\psi K^{(*)}$ channels. The distribution of the missing mass to the $B\pi^{\pm}$ pairs shows clear signals of the $\Upsilon(5S) \to [B\bar{B}^*]^{\pm}\pi^{\mp}$ and $\Upsilon(5S) \to [B^*\bar{B}^*]^{\pm}\pi^{\mp}$ decays [see Fig. 7 (a)]; corresponding branching fractions of $(2.83 \pm 0.29 \pm 0.46)\,\%$ and $(1.41 \pm 0.19 \pm 0.24)\,\%$, respectively, are in agreement with previous Belle measurement [30]. No signal of the $\Upsilon(5S) \to [B\bar{B}]^{\pm}\pi^{\mp}$ decay is found, with upper limit on its fraction of $< 0.4\%$ at 90% confidence level.

The distributions in the $B\bar{B}^*$ and $B^*\bar{B}^*$ invariant mass for the $\Upsilon(5S) \to [B\bar{B}^*]^{\pm}\pi^{\mp}$ and $\Upsilon(5S) \to [B^*\bar{B}^*]^{\pm}\pi^{\mp}$ signal regions, respectively, indicate clear excess of events over background, peaking at the thresholds [see Fig. 7 (b) and (c)]. These threshold peaks are the signals of the $Z_b(10610) \to B\bar{B}^*$ and $Z_b(10650) \to B^*\bar{B}^*$ decays, with significances of $8\,\sigma$ and $6.8\,\sigma$, respectively. Despite much larger phase-space, no significant signal of the $Z_b(10650) \to B\bar{B}^*$ decay was found.

Assuming that the Z_b decays are saturated by the observed so far channels, Belle calculated relative branching fractions of the $Z_b(10610)$ and $Z_b(10650)$ (see Table 1). The $B^{(*)}\bar{B}^*$ channel is

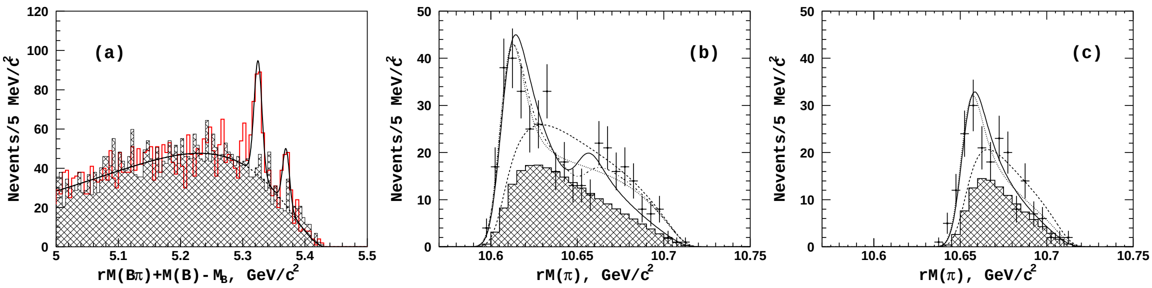

Figure 7: Missing mass to the pairs formed from the reconstructed B candidate and charged pion (a) and missing mass to the charged pions for the $B\pi$ combinations for (b) $\Upsilon(5S) \to B\bar{B}^*\pi$ and (c) $\Upsilon(5S) \to B^*\bar{B}^*\pi$ candidate events.

Table 1: Branching fractions ($\mathscr{B}$) of $Z_b(10610)$ and $Z_b(10650)$ assuming that the observed so far channels saturate it.

Channel	$\mathscr{B}$ of $Z_b(10610)$, %	$\mathscr{B}$ of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	2.15 ± 0.56	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

dominant and accounts for about 80% of the Z_b decays.

Both $Z_b(10610)$ and $Z_b(10650)$ are isotriplets with only charged components observed originally. Belle searched for their neutral components using the $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ ($n = 1,2$) decays [31]. These decays were observed for the first time, measured branching fractions $\mathscr{B}[\Upsilon(5S) \to \Upsilon(1S)\pi^0\pi^0] = (2.25 \pm 0.11 \pm 0.22) \times 10^{-3}$ and $\mathscr{B}[\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0] = (3.66 \pm 0.22 \pm 0.48) \times 10^{-3}$, are approximately two times smaller than the corresponding $\mathscr{B}[\Upsilon(5S) \to \Upsilon(1S,2S)\pi^+\pi^-]$, in agreement with the isospin relations.

Belle performed the Dalitz plot analyses of the $\Upsilon(5S) \to \Upsilon(1S,2S)\pi^0\pi^0$ transitions. The $Z_b(10610)^0$ signal was found in the $\Upsilon(2S)\pi^0$ channel with the significance of $5.3\,\sigma$ ($4.9\,\sigma$ including systematics). The $Z_b(10610)^0$ mass of $(10609^{+8}_{-6} \pm 6)\,\mathrm{MeV}/c^2$ is consistent with the charged $Z_b(10610)^\pm$ mass. The signal of the $Z_b(10610)^0$ in the $\Upsilon(1S)\pi^0$ channel and the $Z_b(10650)^0$ signal are insignificant. The Belle data do not contradict the existence of the above signals, but the available statistics are insufficient to establish them.

Proposed interpretations of the $Z_b(10610)$ and $Z_b(10650)$ include the compact tetraquark [32], non-resonant rescattering [33], multiple rescatterings that result in a pole in the amplitude, known as coupled channel resonance [34] and deutron-like molecule bound by meson exchanges [35]. All these mechanisms (except for the tetraquark) are intimately related and correspond rather to quantitative differences then to qualitative ones. Further experimental and theoretical studies are needed to clarify the nature of the Z_b states.

Despite observed only recently, Z_b states provide a very rich phenomenological object with a lot of experimental information available. They could be very useful for understanding dynamics of the hadronic systems near open flavor thresholds.

2.3 Light quarkonium near $K\bar{K}$ threshold

The BESIII Collaboration observed the $\eta(1405) \to f_0(980)\pi^0$ decay with high rate, corresponding to a strong isospin violation [36]. The rate is much higher than can be expected from the $a_0(980)$-$f_0(980)$ mixing. Proposed explanation is the triangular singularity mechanism [37], in which contributions of different $K^*\bar{K}$ rescattering "triangle" diagrams do not cancel close to the $K\bar{K}$ threshold due to an isospin-violating mass difference between the K^0 and K^+ mesons. This mechanism explains also much lower measured $f_0(980)$ width compared to the world average [7].

3. Quarkonium(-like) states above open flavor thresholds

Many recently observed states above the open flavor thresholds exhibit anomalously large rates of transitions to lower quarkonia with emission of hadrons. There are four such well-established states in charmonium sector: the $Y(3915)$ observed in the $J/\psi\omega$ channel in B meson decays and in $\gamma\gamma$ fusion [38], and the states observed in the initial state radiation (ISR) process: $Y(4260) \to J/\psi\pi^+\pi^-$ [39] and $Y(4360,4660) \to \psi(2S)\pi^+\pi^-$ [40]. Recently BaBar confirmed several signals observed earlier by Belle (the $\gamma\gamma \to Y(3915)$ process [41] and the $Y(4660)$ signal [42]). BaBar also updated the measurement of the $Y(4260)$ properties and did not confirm the $Y(4008)$ state reported by Belle [43].

Belle has measured for the first time the $e^+e^- \to J/\psi\eta$ cross-section using the ISR process [44]. Belle finds two peaking structures that are interpreted as the $\psi(4040) \to J/\psi\eta$ and $\psi(4160) \to J/\psi\eta$ signals (see Fig. 8). The partial widths of these transitions are $\Gamma \sim 1\,\mathrm{MeV}$,

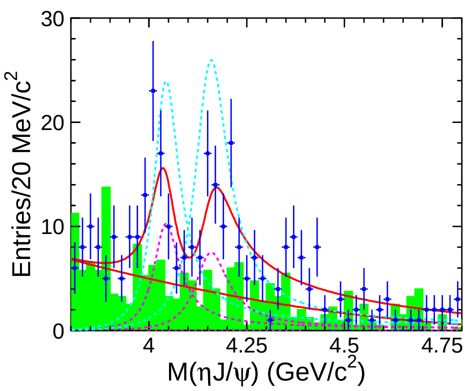

Figure 8: The $\eta J/\psi$ invariant mass distribution and the fit results. The points with error bars show the data while the shaded histogram is the normalized η and J/ψ background from the sidebands. The curves show the best fit on signal candidate events and sideband events simultaneously and the contribution from each Breit-Wigner component.

which is anomalously large. For the first time the "ordinary" ψ states that were successfully described so far as simple $c\bar{c}$ bound states, show anomalous properties.

Similar phenomenon has been found also in bottomonium sector: in 2008 Belle observed anomalously large rates of the $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1,2,3$) transitions with partial widths of $300-400\,\mathrm{keV}$ [2]. Recently Belle reported preliminary results on the observation of $\Upsilon(5S) \to \Upsilon(1S,2S)\eta$ and $\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$ with anomalously large rates. There is a similar phenomenon also in the $s\bar{s}$ sector: in 2006 BaBar found a new resonance $\phi(2170)$ decaying to the $\phi f_0(980)$ channel [45].

It is proposed that these anomalies are due to the contribution of the hadron loops [46, 47]. The phenomenon can be considered either as a rescattering of the $D\bar{D}$ or $B\bar{B}$ mesons, or as a contribution of the four-quark molecular component to the quarkonium wave-function. Large ratio of the $\Upsilon(4S) \to \Upsilon(1S)\eta$ decays observed in 2010 by BaBar could have similar explanation [48].

Despite striking similarity between the observations in the charmonium and bottomonium sectors, there is also some difference. In charmonium, each of the $Y(3915)$, $\psi(4040)$, $\psi(4160)$, $Y(4260)$, $Y(4360)$ and $Y(4660)$ decays to only one particular decay channel [$J/\psi\omega$, $J/\psi\eta$, $J/\psi\pi^+\pi^-$ or $\psi(2S)\pi^+\pi^-$]. In bottomonium, we know only one state with anomalous properties, the $\Upsilon(5S)$, that decays to many different channels [$\Upsilon(nS)\pi^+\pi^-$, $h_b(mP)\pi^+\pi^-$, $\Upsilon(1D)\pi^+\pi^-$, $\Upsilon(nS)\eta$] with similar probabilities for each channel. There is no general model giving explanation to this difference between charmonium and bottomonium. To explain affinity of the charmonium-like states to some particular channels, the notion of "hadrocharmonium" was proposed [49]. It is a heavy quarkonium embedded into a cloud of light hadron(s), thus the fall-apart decay could be dominant. Hadrocharmonium could also provide an explanation for the charged charmonium-like states discussed below.

3.1 Charged charmonium-like states

In 2007-2009 the Belle Collaboration observed three charged charmonium-like states $Z(4430)^\pm \to \psi(2S)\pi^\pm$, $Z(4050/4250)^\pm \to \chi_{c1}\pi^\pm$ using B decays $B^+ \to ZK^+$ [50]. The BaBar data do not contradict the Belle data, however BaBar does not confirm these states [51]. This experimental controversy can be lifted by LHCb in case of the $Z(4430)^\pm$, while clarification of the $Z(4050/4250)^\pm$ status will have to wait for the next generation B-factory.

3.2 Double charmonium production

For completeness, we would like to mention the $X(3940)$ and $X(4160)$ states from double charmonium production process $e^+e^- \to J/\psi X(3940/4160)$, that decay to $D\bar{D}^*$ and $D^*\bar{D}^*$ channels, respectively. They were observed by Belle in 2005-2007 [52]. The BaBar Collaboration has not reported any studies of these processes yet.

4. Baryons

There is a significant progress with the studies of the baryons.

4.1 Heavy baryons

Until recently experimental knowledge of the baryons containing the b quark was limited to the S-wave ground states, that were observed at the TEVATRON. The LHCb Collaboration observed the first P-wave excitations in the Λ_b family [53] in the $\Lambda_b\pi^+\pi^-$ channel (see Fig. 9 left), with $\Lambda_b \to \Lambda_c^+\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$. The $1.0\,\mathrm{fb}^{-1}$ data sample was used. Significances of the new states

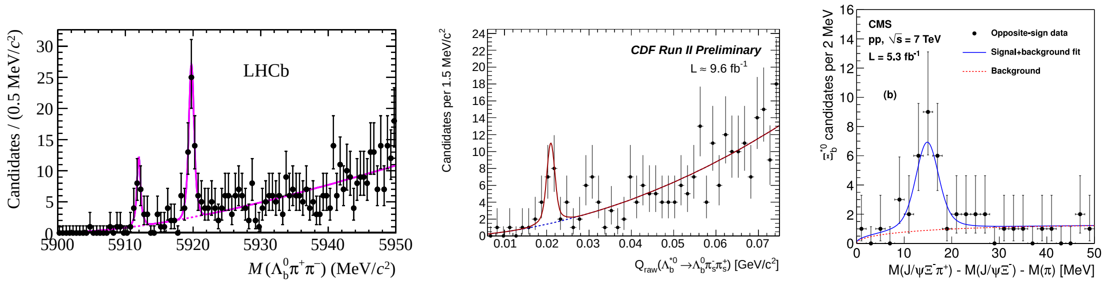

Figure 9: The mass of the $\Lambda_b\pi^+\pi^-$ candidates at LHCb (left) and CDF (middle). The mass of the $\Xi_b^-\pi^+$ candidates at CMS (right).

are $5.2\,\sigma$ and $10.2\,\sigma$ including systematics and trial factor. Measured masses are $(5911.97 \pm 0.12 \pm 0.02 \pm 0.66)\,\mathrm{MeV}/c^2$ and $(5919.77 \pm 0.08 \pm 0.02 \pm 0.66)\,\mathrm{MeV}/c^2$ (third uncertainty is due to the Λ_b^0 mass); widths are consistent with zero, $\Gamma < 0.7\,\mathrm{MeV}$ at 90% confidence level. The new states are called $\Lambda_b^{*0}(5912)$ and $\Lambda_b^{*0}(5920)$. They are interpreted as heavy-quark symmetry partners with $J^P = 1/2^-$ and $3/2^-$, respectively, and with light diquark in a $^1S_0$ state and in a P-wave relative to the heavy quark.

The $\Lambda_b^{*0}(5920)$ was confirmed by CDF (see Fig. 9 middle) [54], measured mass $(5919.5 \pm 0.35 \pm 1.72)\,\mathrm{MeV}/c^2$ is consistent with LHCb.

The CMS Collaboration observed new baryon [55] in the $\Xi_b^-\pi^+$ channel (see Fig. 9 right), with $\Xi_b^- \to J/\psi\Xi^- \to \mu^+\mu^-\Lambda^0\pi^-$ using $5.3\,\mathrm{fb}^{-1}$ of data. The significance is above $5\,\sigma$ level, measured mass difference is $M(\Xi_b^-\pi^+) - m_{\Xi_b} - m_\pi = (14.84 \pm 0.74 \pm 0.28)\,\mathrm{MeV}/c^2$. The new state most likely corresponds to the $J^P = 3/2^+$ spin-excitation of the Ξ_b.

4.2 Light-quark baryons

The BESIII Collaboration reported the partial wave analysis of the $\psi(3686) \to p\bar{p}\pi^0$ decays. In this decay, two new resonances are observed, one $1/2^+$ resonance with a mass of $(2300^{+40+109}_{-30-0})$ MeV/c^2 and width of $(340^{+30+110}_{-30-58})\,\mathrm{MeV}$, and one $5/2^-$ resonance with a mass of (2570^{+19+34}_{-10-10}) MeV/c^2 and width of $(250^{+14+69}_{-24-21})\,\mathrm{MeV}$. This is the first partial wave analysis result on baryons from BESIII.

5. Summary

The particle spectroscopy enjoys intensive flood of new results.

In the heavy quarkonium sector the number of spin-singlet bottomonium states has increased from one to four over the last two years, including more precise measurement of the $\eta_b(1S)$ mass which appeared to be $11\,\mathrm{MeV}/c^2$ away from the PDG2012 average. There is an evidence of one of the two still missing narrow charmonium states expected in the region between the $D\bar{D}$ and $D\bar{D}^*$ thresholds. Observation and detailed studies of the *charged* bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ open reach phenomenological field to study exotic states near open flavor thresholds. There is also significant progress and more clear experimental situation with the highly excited heavy quarkonium states above open flavor thresholds. General feature of many of such states is their large decay rates to lower quarkonia with the emission of light hadrons. Hadron loops are important for understanding of their properties, however, there is no general theoretical model for these highly excited states yet. There remain open questions or experimental controversies (like charged charmonium-like states) which are within the reach of the LHC or will have to wait for the next generation B-factory.

BESIII produces many interesting results in the light-quark and charmonium spectroscopy.

There are three new heavy baryons from the LHC and TEVATRON, that correspond to the spin-excitation in the Ξ_b system and the first P-wave excitations in the Λ_b system. There are two new highly excited baryons from BESIII.

The bottom line is that the low excitations are in agreement with the Lattice QCD or effective theories calculations, while high excitations show some unexpected properties, which are still not well understood. Interestingly, similar phenomena near and above open flavor thresholds are found in bottomonium, charmonium and strangeonium sectors.

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