DEVELOPMENTS IN HEAVY QUARKONIUM SPECTROSCOPY

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A golden age for heavy quarkonium physics dawned at the turn of this century, initiated by the confluence of exciting advances in quantum chromodynamics (QCD) and an explosion of related experimental activity. The subsequent broad spectrum of breakthroughs, surprises, and continuing puzzles had not been anticipated. In that period, the BESII program concluded only to give birth to BESIII; the B-factories and CLEO-c flourished; quarkonium production and polarization measurements at HERA and the Tevatron matured; and heavy-ion collisions at RHIC opened a window on the deconfinement regime. Recently also ATLAS, CMS and LHCb started to contribute to the field. For an extensive presentation of the status of heavy quarkonium physics, the reader is referred to several reviews [1–7], the last of which covers developments through the middle of 2010, and which supplies some tabular information and phrasing reproduced here (with kind permission, copyright 2011, Springer). This note focuses solely on experimental developments in heavy quarkonium spectroscopy, and in particular on those too recent to have been included in Ref. 7.

In this mini-review we display the newly discovered states, where “newly” is interpreted to include the period since 2003. In earlier versions of this write-up the particles were sorted according to an assumed *conventional* or *unconventional* nature with respect to the quark model. However, since this classification is not always unambiguous, we here follow Ref. [8] and sort the states into three groups, namely states below (*cf.* Table 1), near (*cf.* Table 2) and above (*cf.* Table 3) the lowest open flavor thresholds.

Table 1 lists properties of newly observed heavy quarkonium states located below the lowest open flavor thresholds. Those are expected to be (at least prominently) conventional quarkonia. The h_c is the ${}^1P_1$ state of charmonium, singlet partner of the long-known χ_{cJ} triplet ${}^3P_J$. The $\eta_c(2S)$ is the first excited state of the pseudoscalar ground state $\eta_c(1S)$, lying just below the mass of its vector counterpart, $\psi(2S)$. The ground state of bottomonium is the $\eta_b(1S)$, recently confirmed with a second observation of more than 5σ significance at Belle. In addition, in the same experiment strong evidence was collected for $\eta_b(2S)$ [29], but it still needs experimental confirmation at the 5σ level. The $\Upsilon(1D)$ is the lowest-lying D-wave triplet of the $b\bar{b}$ system. Both the $h_b(1P)$, the bottomonium counterpart of $h_c(1P)$, and the next excited state, $h_b(2P)$, were recently observed by Belle [31], as described further below, in dipion transitions from either the $\Upsilon(10860)$ or $Y_b(10888)$. In addition, Belle recently reported a measurement of $\psi_2(1D)$ which would be a $J^{PC} = 2^{+-}$ state [22]. While the negative C-parity is indeed established by the measurement, the assignment of $J = 2$ was done by matching to the closest quark model state. In the table this state is therefore simply called $X(3823)$, according to the PDG name convention. After the mass of the $\eta_b(1S)$ was shifted upwards by about 11 MeV based on a new Belle measurement [29], all states mentioned in this paragraph fit into their respective spectroscopies roughly where expected. Their exact masses, production mechanisms, and decay modes provide guidance to their descriptions within QCD.

There is a large number of newly discovered states both near and above the lowest open flavor thresholds. They are displayed in Table 2 and Table 3, respectively*; notice that just a few of them have been confirmed experimentally. With the possible exception of the tensor state located at 3930 MeV, neither can unambiguously be assigned a place in the hierarchy of charmonia or bottomonia nor has a universally accepted unconventional origin. The $X(3872)$ is widely studied, yet its interpretation demands additional experimental attention: after the quantum numbers were fixed at LHCb [54] the next experimental challenge will be a measurement of its line shape.

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[*] For consistency with the literature, we preserve the use of X, Y and Z, contrary to the practice of the PDG, which exclusively uses X for unidentified states.

The state originally dubbed $Z(3930)$ is now regarded by many as the first observed $2P$ state of χ_{cJ}, the $\chi_{c2}(2P)$. The scalar state at 3915 MeV is now called $\chi_{c0}(3915)$. It might be the first radial excitation of $\chi_{c0}(1P)$, but this interpretation is not generally accepted [100]. The $Y(4260)$ and $Y(4360)$ are vector states decaying to $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$, respectively, yet, unlike most conventional vector charmonia, do not correspond to enhancements in the e^+e^- hadronic cross section.

Based on a full amplitude analysis of the $B^0 \to K^+\pi^-\psi(2S)$ decays, Belle determined the spin-parity of the $Z(4430)^{\pm}$** to be $J^P = 1^+$ [92]. Very recently this state as well as its quantum numbers were confirmed at LHCb [94] with much higher statistics. Improved values for mass and width from LHCb are consistent with earlier measurements; our new average is in Table 3; the experiment even reports a resonant behavior of the $Z(4430)^{\pm}$ amplitude. This state as well as $Z(4050)^{\pm}$ and $Z(4250)^{\pm}$ seen in $\pi^{\pm}\chi_{c1}$ are, however, not confirmed (nor excluded) by BaBar (see [93] for the $Z(4430)$ and [74] for the $Z(4050)^{\pm}$ and $Z(4250)^{\pm}$). Belle observes signals of significances 5.0σ, 5.0σ, and 6.4σ for $Z_1(4050)^+$, $Z_2(4250)^+$, and $Z(4430)^+$, respectively, whereas BABAR reports 1.1σ, 2.0σ, and 2.4σ effects, setting upper limits on product branching fractions that are not inconsistent with Belle's and LHCb's measured rates. For $Z_1(4050)^+$ and $Z_2(4250)^+$ the situation remains unresolved.

In addition to the three Z_c^+ discussed in the previous paragraph, in 2013 two more states named $Z_c(3900)^+$ and $Z_c(4020)^+$ were unearthed in the charmonium region. Note that in this write-up as well as the RPP listings we combined $Z_c(3900)^+$ (seen in $J/\psi\pi\pi$) and $Z_c(3885)^+$ (seen in $D\bar{D}^*$) as well as $Z_c(4020)^+$ (seen in $h_c\pi\pi$) and $Z_c(4025)^+$ (seen in $D^*\bar{D}^*$) into only two states due to their close proximity in mass. In various respects $Z_c(3900)^+$ and $Z_c(4020)^+$ seem to be the charmed partners of $Z_b(10610)^+$ and $Z_b(10650)^+$ as will be outlined below.

** There are currently various candidates for isotriplet states in the spectrum. For some of them both charged states are already established and sometimes there is also evidence for the neutral partner. We still chose to put the charge as superscript since it is an explicit marker of the exotic nature of the states.

Table 1: New states below the open flavor thresholds in the $c\bar{c}$, $b\bar{c}$, and $b\bar{b}$ regions, ordered by mass. Masses m and widths Γ represent the weighted averages from the listed sources. Quoted uncertainties reflect quadrature summation from individual experiments. Ellipses (...) in the Process column indicate inclusively selected event topologies; *i.e.*, additional particles not required by the Experiments to be present. A question mark (?) indicates an unmeasured value. For each Experiment a citation is given, as well as the statistical significance (#σ), or "(np)" for "not provided". The Year column gives the date of the first measurement cited. The Status column indicates that the state has been observed by at most one (NC!-needs confirmation) or at least two independent experiments with significance of $>5\sigma$ (OK). The state labelled $\chi_{c2}(2P)$ has previously been called $Z(3930)$. In the publication $X(3823)$ is called $\psi_2(1D)$, however, only the C–parity is measured; $J^P = 2^+$ are assigned from quark model. Adapted from [7] with kind permission, copyright (2011), Springer, and [8] with kind permission from the authors.

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$h_c(1P)$	3525.41 ± 0.16	<1	1^{+-}	$\psi(2S) \to \pi^0\,(\gamma\eta_c(1S))$	CLEO [9–11] (13.2)	2004	OK
				$\psi(2S) \to \pi^0\,(\gamma ...)$	CLEO [9–11] (10), BES [12] (19)		
				$p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$	E835 [13] (3.1)		
				$\psi(2S) \to \pi^0\,(...)$	BESIII [12] (9.5)		
$\eta_c(2S)$	3638.9 ± 1.3	10±4	0^{-+}	$B \to K\,(K^0_S K^- \pi^+)$	Belle [14,15] (6.0)	2002	OK
				$e^+e^- \to e^+e^-\,(K^0_S K^- \pi^+)$	BABAR [16,17] (7.8),		
					CLEO [18] (6.5), Belle [19] (6)		
				$e^+e^- \to J/\psi\,(...)$	BABAR [20] (np), Belle [21] (8.1)		
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\gamma\,\chi_{c1})$	Belle [22](3.8)	2013	NC!
B_c^+	6277 ± 6	-	0^-	$\bar{p}p \to (\pi^+ J/\psi)...$	CDF [23,24] (8.0), D0 [25] (5.2)	2007	OK
$\eta_b(1S)$	9395.8 ± 3.0	$12.4^{+12.7}_{-5.7}$	0^{-+}	$\Upsilon(3S) \to \gamma\,(...)$	BABAR [26] (10), CLEO [27] (4.0)	2008	OK
				$\Upsilon(2S) \to \gamma\,(...)$	BABAR [28] (3.0)		
				$h_b(1P, 2P) \to \gamma\,(...)$	Belle [29](14)	2012	NC!
				$\Upsilon(10860) \to \pi^+\pi^-\gamma\,(...)$	Belle [30] (14)		
$h_b(1P)$	9898.6 ± 1.4	?	1^{+-}	$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [31,30] (5.5)	2011	NC!
				$\Upsilon(3S) \to \pi^0\,(...)$	BABAR [32] (3.0)		
$\eta_b(2S)$	9999 ± 4	< 24	0^{-+}	$h_b(2P) \to \gamma\,(...)$	Belle [29](4.2)	2012	NC!
$\Upsilon(1^3D_2)$	10163.7 ± 1.4	?	2^{--}	$\Upsilon(3S) \to \gamma\gamma\,(\gamma\gamma\Upsilon(1S))$	CLEO [33] (10.2)	2004	OK
				$\Upsilon(3S) \to \gamma\gamma\,(\pi^+\pi^-\Upsilon(1S))$	BABAR [34] (5.8)		
				$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [31] (2.4)		
$h_b(2P)$	$10259.8^{+1.5}_{-1.2}$	?	1^{+-}	$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [31,30] (11.2)	2011	NC!
$\chi_{bJ}(3P)$	10530 ± 10	?	?	$pp \to (\gamma\mu^+\mu^-)...$	ATLAS [35] (>6), D0 [36] (3.6)	2011	OK

Although $\eta_c(2S)$ measurements began to converge towards a mass and a width some time ago, refinements are still in progress. In particular, Belle [15] has revisited its analysis of $B \to K\eta_c(2S)$, $\eta_c(2S) \to KK\pi$ decays with more data and methods that account for interference between the above decay chain, an equivalent one with the $\eta_c(1S)$ instead, and one with no intermediate resonance. The net effect of this interference is far from trivial; it shifts the apparent mass by $\sim$+10 MeV and blows up the apparent width by a factor of six. The updated $\eta_c(2S)$ mass and width are in better accordance with other measurements than the previous treatment [14], which did not include interference. Complementing this measurement in B-decay, BABAR [16] updated their previous [17] $\eta_c(2S)$ mass and width measurements in two-photon production, where interference effects, judging from studies of $\eta_c(1S)$, appear to be small. In combination, precision on the $\eta_c(2S)$ mass has improved dramatically.

The $Y(4140)$ observed in 2008 by CDF [75,76] was confirmed at CMS and D0 [79,80], however, a second structure related to $Y(4274)$ could not be established unambiguously. The two states were neither seen in B decays at Belle [77] and LHCb [78] nor in $\gamma\gamma$ collisions at Belle [87]. Thus the situation for $Y(4140)$ and $Y(4274)$ is still controversial.

New results on η_b, h_b, and Z_b^+ mostly come from Belle, all from analyses of 121.4 fb^{-1} of e^+e^- collision data collected near the peak of the $\Upsilon(10860)$ resonance. They all appear in the same types of decay chains: $\Upsilon(10860) \to \pi^- Z_b^+$, $Z_b^+ \to \pi^+(b\bar{b})$, and, when the $b\bar{b}$ forms an $h_b(1P)$, frequently decaying as $h_b(1P) \to \gamma\eta_b$.

The Belle h_b discovery analysis [31] selects hadronic events and searches for peaks in the mass recoiling against $\pi^+\pi^-$ pairs, the spectrum for which, after subtraction of smooth combinatoric and $K_S^0 \to \pi^+\pi^-$ backgrounds, appears in Fig. 1. Prominent and unmistakable $h_b(1P)$ and $h_b(2P)$ peaks are present. This search was directly inspired by a CLEO result [101], which found the surprisingly copious transitions $\psi(4160) \to \pi^+\pi^- h_c(1P)$ and an indication that $Y(4260) \to \pi^+\pi^- h_c(1P)$ occurs at a comparable rate as the signature

Table 2: As in Table 1, but for new states near the first open flavor thresholds in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass. For $X(3872)$, the values given are based only upon decays to $\pi^+\pi^- J/\psi$. Updated from [7] with kind permission, copyright (2011), Springer, and [8] with kind permission from the authors.

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K\,(\pi^+\pi^- J/\psi)$	Belle [37,38] (12.8), BABAR [39] (8.6)	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [40–42] (np), D0 [43] (5.2)		
				$B \to K\,(\omega J/\psi)$	Belle [44] (4.3), BABAR [45] (4.0)		
				$B \to K\,(D^{*0}\overline{D}^0)$	Belle [46,47] (6.4), BABAR [48] (4.9)		
				$B \to K\,(\gamma J/\psi)$	Belle [49] (4.0), BABAR [50,51] (3.6), LHCb [52] (>10)		
				$B \to K\,(\gamma\psi(2S))$	BABAR [51] (3.5), Belle [49] (0.4), LHCb [52] (4.4)		
				$pp \to (\pi^+\pi^- J/\psi) + ...$	LHCb [53,54] (np)		
$Z_c(3900)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BESIII [55](np)	2013	NC!
	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BESIII [56](8), Belle [57](5.2) T. Xiao *et al.* [CLEO data] [58](>5)	2013	OK
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BESIII [59](8.9)	2013	NC!
	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BESIII [60](10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [61,62,63](>10)	2011	OK
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [62](16)	2011	OK
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [64](8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [61,62](>10)	2011	OK
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [62](16)	2011	OK
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [64](6.8)	2012	NC!

mode, $Y(4260) \to \pi^+\pi^- J/\psi$. The presence of $\Upsilon(nS)$ peaks in Fig. 1 at rates two orders of magnitude larger than expected for transitions requiring a heavy-quark spin-flip, along with separate studies with exclusive decays $\Upsilon(nS) \to \mu^+\mu^-$, allow precise calibration of the $\pi^+\pi^-$ recoil mass spectrum and very accurate measurements of $h_b(1P)$ and $h_b(2P)$ masses. Both corresponding hyperfine splittings are consistent with zero within an uncertainty of about 1.5 MeV (lowered to ±1.1 MeV for $h_b(1P)$ in Ref. [30]) .

Table 3: As in Table 1, but for new states above the first open flavor thresholds in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass. $X(3945)$ and $Y(3940)$ have been subsumed under $X(3915)$ due to compatible properties. The quantum numbers of the state were measured at BaBar [65]. The state known as $Z(3930)$ appears as the $\chi_{c2}(2P)$ in Table 1. In some cases experiment still allows two J^{PC} values, in which case both appear. See also the reviews in [1–7]. Updated from [7] with kind permission, copyright (2011), Springer, and [8] with kind permission from the authors.

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$\chi_{c0}(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B \to K\,(\omega J/\psi)$	Belle [66] (8.1), BABAR [67,65] (19)	2004	OK
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [68] (5.3), BABAR [69,45] (5.8)	2005	OK
				$e^+e^- \to e^+e^-\,(\omega J/\psi)$	Belle [70] (7.7), BABAR [45] (np)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\overline{D}^*)$	Belle [71] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\,(...)$	Belle [21] (5.0)		
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [72] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [73] (5.0), BABAR [74] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [75,76](5.0), Belle [77](1.9), LHCb [78](1.4), CMS [79](>5) D0 [80](3.1)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\overline{D}^*)$	Belle [71] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [73] (5.0), BABAR [74] (2.0)	2008	NC!
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^- J/\psi)$	BABAR [81,82] (8.0) CLEO [83] (5.4), Belle [72] (15)	2005	OK
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [84] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [84] (5.1)		
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [85](np), Belle [57](np)	2012	OK
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BESIII [56](8), Belle [57](5.2)	2013	OK
				$e^+e^- \to (\gamma\,X(3872))$	BESIII [86](5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [76](3.1), LHCb [78](1.0), CMS [79](>3), D0 [80](np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(\phi J/\psi)$	Belle [87] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	BABAR [88] (np), Belle [89] (8.0)	2007	OK
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [90,91,92](6.4), BaBar [93](2.4)	2007	OK
				$B^0 \to \psi(2S)\pi^- K^+$	LHCb [94](13.9)		
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [95] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	Belle [89] (5.8)	2007	NC!
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi))$	PDG [96]	1985	OK
				$e^+e^- \to (\pi\pi\Upsilon(1S,2S,3S))$	Belle [97,62,63](>10)	2007	OK
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [62,63](>5)	2011	OK
				$e^+e^- \to (\pi Z_b(10610,10650))$	Belle [62,63](>10)	2011	OK
				$e^+e^- \to (\eta\Upsilon(1S,2S))$	Belle [98](10)	2012	OK
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [98](9)	2012	OK
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [99](2.3)	2008	NC!

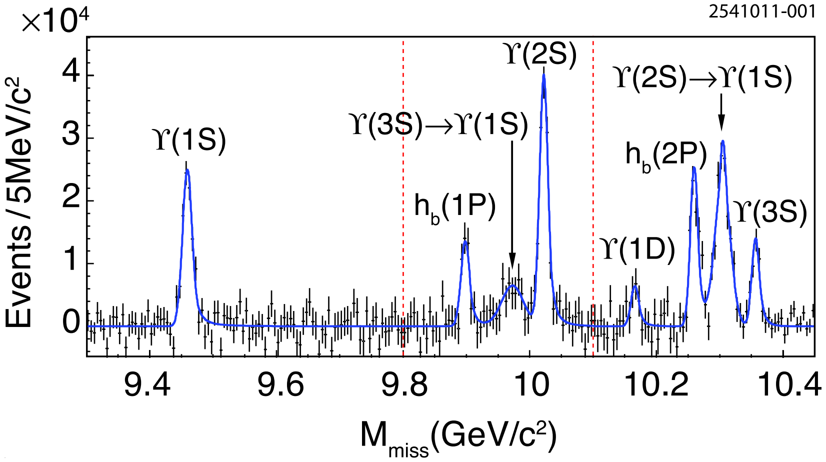

Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, M_{miss}, in e^+e^- collision data taken near the peak of the $\Upsilon(10860)$ (*points with error bars*). The smooth combinatoric and $K_S^0 \to \pi^+\pi^-$ background contributions have already been subtracted. The fit to the various labeled signal contributions overlaid (*curve*). Adapted from [31] with kind permission, copyright (2011) The American Physical Society.

Belle soon noticed that, for events in the peaks of Fig. 1, there seemed to be two intermediate charged states nearby. For example, Fig. 2 shows a Dalitz plot for events restricted to the $\Upsilon(2S)$ region of $\pi^+\pi^-$ recoil mass. The two bands observed in the maximum of the two $M[\pi^\pm\Upsilon(2S)]^2$ values also appear for $\Upsilon(1S)$, $\Upsilon(3S)$, $h_b(1P)$, and $h_b(2P)$ samples but not in the respective $[b\bar{b}]$ sidebands. Belle fits all subsamples to resonant plus non-resonant amplitudes, allowing for interference (notably, between $\pi^-Z_b^+$ and $\pi^+Z_b^-$), and finds consistent pairs of Z_b^+ masses for all bottomonium transitions, and comparable strengths of the two states. A recent angular analysis assigned $J^P = 1^+$ for both Z_b^+ states [102], which must also have negative G-parity. Transitions through Z_b^+ to the $h_b(nP)$ saturate the observed $\pi^+\pi^-h_b(nP)$ cross sections. The two masses of Z_b^+ states are just a few MeV above the $B^*\bar{B}$ and $B^*\bar{B}^*$ thresholds, respectively. Still, they predominantly decay into

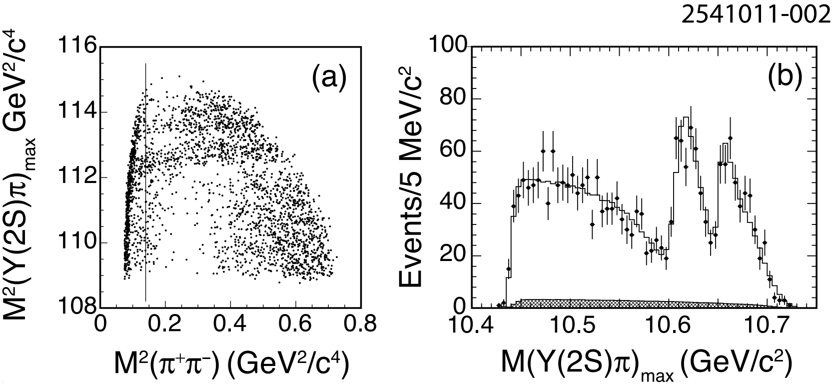

Figure 2: From Belle [62] e^+e^- collision data taken near the peak of the $\Upsilon(10860)$ for events with a $\pi^+\pi^-$-missing mass consistent with a $\Upsilon(nS)2$, (a) the maximum of the two possible single $\pi^\pm$-missing-mass-squared combinations vs. the $\pi^+\pi^-$-mass-squared; and (b) projection of the maximum of the two possible single $\pi^\pm$-missing-mass combinations (*points with error bars*) overlaid with a fit (*curve*). Events to the left of the vertical line in (a) are excluded from further analysis. The two horizontal stripes in (a) and two peaks in (b) correspond to the two Z_b^+ states. Adapted from [62] with kind permission, copyright (2011) The American Physical Society.

these channels [64], regardless the small phase space, with branching fractions that exceed 80% and 70%, respectively, at 90% CL. This feature provides strong evidence for their molecular nature—note that the Z_b^+ states cannot be simple mesons because they are charged and have $b\bar{b}$ content.

The third Belle result to follow from these data is the confirmation of the $\eta_b(1S)$ and measurement of the $h_b(1P) \to \gamma\eta_b(1S)$ branching fraction, expected to be several tens of percent. To accomplish this, events with the $\pi^+\pi^-$ recoil mass in the $h_b(1P)$ mass window and a radiative photon candidate are selected, and the $\pi^+\pi^-\gamma$ recoil mass queried for correlation with non-zero $h_b(1P)$ population in the $\pi^+\pi^-$ missing mass spectrum, as shown in Fig. 3. A clear peak is observed, corresponding to the

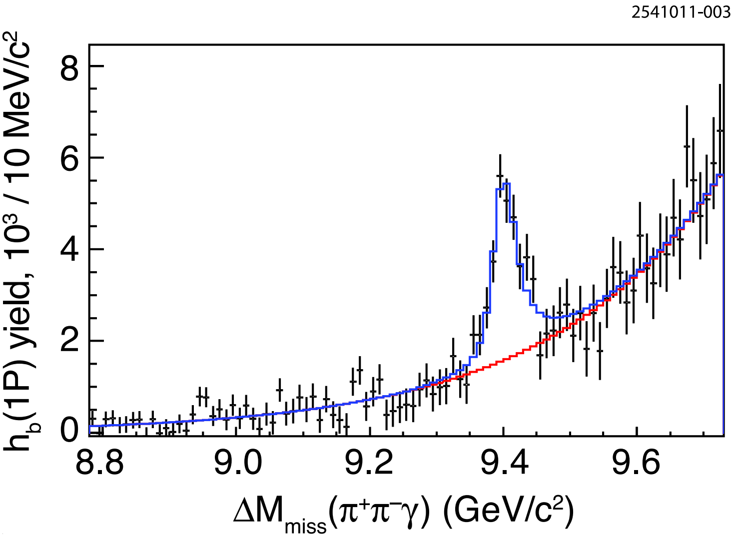

Figure 3: From Belle [30] e^+e^- collision data taken near the peak of the $\Upsilon(10860)$, the $h_b(1P)$ event yield vs. the mass recoiling against the $\pi^+\pi^-\gamma$ (corrected for misreconstructed $\pi^+\pi^-$), where the $h_b(1P)$ yield is obtained by fitting the mass recoiling against the $\pi^+\pi^-$ (*points with error bars*). The fit results (*solid histograms*) for signal plus background and background alone are superimposed. Adapted from [30] with kind permission, copyright (2011) The American Physical Society.

$\eta_b(1S)$. A fit is performed to extract the $\eta_b(1S)$ mass, and determine its width and the branching fraction for $h_b(1P) \to \gamma\eta_b(1S)$ (the latter of which is $(49.8 \pm 6.8^{+10.9}_{-\ 5.2})\%$) for the first time. The mass determination has comparable uncertainty and a larger central value (by 10 MeV, or 2.4σ) than the average of previous measurements, thereby reducing the new world average hyperfine splitting by nearly 5 MeV. An independent experimental confirmation of the shifted mass is very important to pursue.

The $\chi_{bJ}(nP)$ states have recently been observed at the LHC by ATLAS [35] and confirmed by D0 [36] for $n = 1, 2, 3$, although in each case the three J states are not distinguished from one another. Events are sought which have both a photon and an $\Upsilon(1S, 2S) \to \mu^+\mu^-$ candidate which together form a

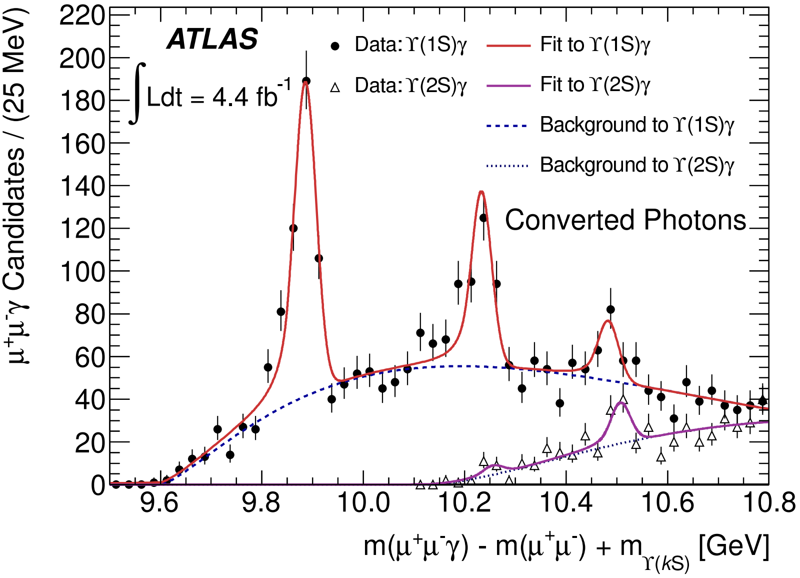

Figure 4: From ATLAS [35] *pp* collision data (*points with error bars*) taken at $\sqrt{s} = 7$ TeV, the effective mass of $\chi_{bJ}(1P, 2P, 3P) \to \gamma\Upsilon(1S, 2S)$ candidates in which $\Upsilon(1S, 2S) \to \mu^+\mu^-$ and the photon is reconstructed as an e^+e^- conversion in the tracking system. Fits (*smooth curves*) show significant signals for each triplet (merged-J) on top of a smooth background. From [35] with kind permission, copyright (2012) The American Physical Society.

mass in the χ_b region. Observation of all three J-merged peaks is seen with significance in excess of 6σ for both unconverted and converted photons. The mass plot for converted photons, which provide better mass resolution, is shown in Fig. 4. This marks the first observation of the $\chi_{bJ}(3P)$ triplet, quite near the expected mass.

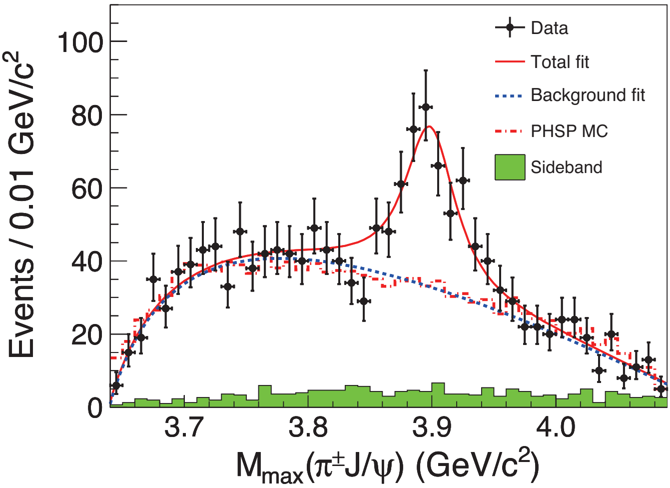

Figure 5: $J/\psi\pi$ invariant mass distributions from BES-III [56] e^+e^- collision data taken near the peak of the $Y(4260)$. Adapted from [56] with kind permission, copyright (2013) The American Physical Society.

In 2013 at BESIII [56] and shortly after at Belle [57] a charged state called $Z_c(3900)^+$ was found near the $D\bar{D}^*$ threshold—the corresponding spectrum from BESIII is shown in Fig. 5. In addition to confirming these findings, Ref. [58] also provided evidence for a neutral partner. A nearby signal was also seen in the $D\bar{D}^*$ channel [55] whose quantum numbers were fixed to 1^{+-}. The masses extracted from these experiments agree only within 2σ. However, since the extraction did not allow for an interference with the background and used Breit-Wigner line shapes, which is not justified near thresholds, there might be some additional systematic uncertainty in the mass values. Therefore in the RPP listings as well as Table 2 both structures appear under the name $Z_c(3900)^+$. Analogously, $Z_c(4020)^+$ (seen in in $h_c\pi\pi$ [59]) and $Z_c^+(4025)$ (seen in $D^*\bar{D}^*$ [60]) are listed as one state, $Z_c(4020)^+$. The Z_c^+ states show some remarkable similarities to the Z_b^+ states, e.g. they decay dominantly to the $D^{(*)}\bar{D}^*$ channels. However, current analyses suggest that the mass of especially the $Z_c(3900)^+$

might be somewhat above the $D\bar{D}^*$ threshold. If confirmed, this feature would clearly challenge a possible $D\bar{D}^*$–molecular interpretation.

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