DEVELOPMENTS IN HEAVY QUARKONIUM SPECTROSCOPY

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A golden age for heavy quarkonium physics dawned a decade ago, 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. 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.

Table 1 lists properties of newly observed conventional heavy quarkonium states, where "newly" is interpreted to mean within the past decade. 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 state originally dubbed $Z(3930)$ is now regarded by many as the first observed $2P$ state of χ_{cJ}, the $\chi_{c2}(2P)$. The first B-meson seen that contains charm is the B_c^+. The ground state of bottomonium is the $\eta_b(1S)$, recently confirmed with a second observation of more than 5σ significance. 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 very recently observed by

Belle [31], as described further below, in dipion transitions from either the $\Upsilon(5S)$ or $Y_b(10888)$. All fit into their respective spectroscopies roughly where expected. Their exact masses, production mechanisms, and decay modes provide guidance to their descriptions within QCD. The $h_b(nP)$ states still need experimental confirmation at the 5σ level, as does the $\chi_{bJ}(3P)$ triplet.

Correspondingly, the menagerie of new, heavy-quarkonium-like *unanticipated* states* is shown in Table 2; notice that just a handful have been experimentally confirmed. None can unambiguously be assigned a place in the hierarchy of charmonia or bottomonia; neither do any have a universally accepted unconventional origin. The $X(3872)$ occupies a unique niche among the unexplained states as both the first and the most intriguing. It is, by now, widely studied, yet its interpretation demands much more experimental attention. 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. The three Z_c^+ and two Z_b^+ states, each decaying to a charged pion and conventional heavy quarkonium state, would be manifestly exotic, but remain unconfirmed. Final states of the type $\Upsilon(nS)\pi^+\pi^-$ from e^+e^- collisions acquired near the $\Upsilon(5S)$ have a lineshape differing somewhat from that of multi-hadronic events, which suggested a new state $Y_b(10888)$, distinct from $\Upsilon(5S)$, which could be analogous to $Y(4260)$. The nature of $Y_b(10888)$, if it does mimic the behavior of the charmonium-region Y's, could help to explain the observed (and otherwise unexpected) high rate of dipion transitions to $\Upsilon(nS)$ and $h_b(nP)$ seen in the e^+e^- collisions near the $\Upsilon(5S)$. It could also provide insight into the Z_b^+ states, which appear to be intermediate resonances in the dipion transitions.

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

Table 1: New *conventional* states 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. In the Process column, the decay mode of the new state claimed is indicated in parentheses. Ellipses (...) 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 in number of standard deviations (#σ), or "(np)" for "not provided". The Year column gives the date of 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 >5σ (OK). The state labelled $\chi_{c2}(2P)$ has previously been called $Z(3930)$. See also the reviews in [1–7]. Adapted from [7] with kind permission, copyright (2011), Springer.

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 [8–10] (13.2)	2004	OK
				$\psi(2S) \to \pi^0\,(\gamma...)$	CLEO [8–10] (10), BES [11] (19)		
				$p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$	E835 [12] (3.1)		
				$\psi(2S) \to \pi^0\,(...)$	BESIII [11] (9.5)		
$\eta_c(2S)$	3638.9 ± 1.3	10±4	0^{-+}	$B \to K\,(K^0_S K^-\pi^+)$	Belle [13,14] (6.0)	2002	OK
				$e^+e^- \to e^+e^-\,(K^0_S K^-\pi^+)$	BABAR [15,16] (7.8),		
					CLEO [17] (6.5), Belle [18] (6)		
				$e^+e^- \to J/\psi\,(...)$	BABAR [19] (np), Belle [20] (8.1)		
$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [21] (5.3), BABAR [22,23] (5.8)	2005	OK
B_c^+	6277 ± 6	-	0^-	$\bar{p}p \to (\pi^+ J/\psi)...$	CDF [24,25] (8.0), D0 [26] (5.2)	2007	OK
$\eta_b(1S)$	9395.8 ± 3.0	$12.4^{+12.7}_{-5.7}$	0^{-+}	$\Upsilon(3S) \to \gamma\,(...)$	BABAR [27] (10), CLEO [28] (4.0)	2008	OK
				$\Upsilon(2S) \to \gamma\,(...)$	BABAR [29] (3.0)		
				$\Upsilon(5S) \to \pi^+\pi^-\gamma\,(...)$	Belle [30] (14)		
$h_b(1P)$	9898.6 ± 1.4	?	1^{+-}	$\Upsilon(5S) \to \pi^+\pi^-\,(...)$	Belle [31,30] (5.5)	2011	NC!
				$\Upsilon(3S) \to \pi^0\,(...)$	BABAR [32] (3.0)		
$\Upsilon(1^3D_2)$	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)		
				$\Upsilon(5S) \to \pi^+\pi^-\,(...)$	Belle [31] (2.4)		
$h_b(2P)$	$10259.8^{+1.5}_{-1.2}$	?	1^{+-}	$\Upsilon(5S) \to \pi^+\pi^-\,(...)$	Belle [31] (11.2)	2011	NC!
$\chi_{bJ}(3P)$	10530 ± 10	?	?	$pp \to (\gamma\mu^+\mu^-)...$	ATLAS [35] (>6)	2011	NC!

BABAR [71,59] has searched for the three $Z_c^{\pm}$ states in the charmonium mass region seen by Belle, and failed to observe any significant signals. The approach taken in searching for $B \to Z^{\pm}K \to (c\bar{c})K\pi$, where $(c\bar{c})$ is $\psi(2S)$ or χ_{c1}, is to first fit the data for all reasonable $K\pi$ mass or angular structure, having demonstrated that the presence of one or more Z's cannot be accommodated by this procedure. After doing so, the finding is that some of what might be the Belle excess of events above Belle background gets absorbed into the $K\pi$ structure of the BABAR background. As shown in Table 2, where Belle observes signals of significances 5.0σ, 5.0σ, and 6.4σ for $Z_1(4050)^+$, $Z_2(4250)^+$, and $Z(4430)^+$, respectively, BABAR reports 1.1σ, 2.0σ, and 2.4σ effects, setting upper limits on product branching fractions that are not inconsistent with Belle's measured rates, leaving the situation unresolved.

Although $\eta_c(2S)$ measurements began to converge on a mass and width nearly a decade ago, refinements are still in progress. In particular, Belle [14] 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 [13] not including interference. Complementing this measurement in B-decay, BABAR [15] updated their previous [16] $\eta_c(2S)$ 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.

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 $\Upsilon(5S)$ resonance. They also appear in the same types of decay chains: $\Upsilon(5S) \to \pi^- Z_b^+$, $Z_b^+ \to \pi^+(b\bar{b})$, and, when the $b\bar{b}$ forms an $h_b(1P)$, frequently $h_b(1P) \to \gamma\eta_b$.

Table 2: As in Table 1, but for new *unconventional* states 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 $\pi^+\pi^- J/\psi$. $X(3945)$ and $Y(3940)$ have been subsumed under $X(3915)$ due to compatible properties. 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]. Adapted from [7] with kind permission, copyright (2011), Springer.

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68±0.17	<1.2	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [36,37] (12.8), BABAR [38] (8.6)	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [39–41] (np), D0 [42] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [43] (4.3), BABAR [23] (4.0)		
				$B \to K(D^{*0}\overline{D}^0)$	Belle [44,45] (6.4), BABAR [46] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [47] (4.0), BABAR [48,49] (3.6)		
				$B \to K(\gamma\psi(2S))$	BABAR [49] (3.5), Belle [47] (0.4)		
				$pp \to (\pi^+\pi^- J/\psi) + ...$	LHCb [50] (np)		
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [51] (8.1), BABAR [52] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [53] (7.7), BABAR [23] (np)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\overline{D}^*)$	Belle [54] (6.0)	2007	NC!
				$e^+e^- \to J/\psi(...)$	Belle [20] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\overline{D})$	BABAR [55] (np), Belle [56] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [57] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), BABAR [59] (1.1)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [60,61] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\overline{D}^*)$	Belle [54] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), BABAR [59] (2.0)	2008	NC!
$Y(4260)$	4263^{+8}_{-9}	95±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [62,63] (8.0)	2005	OK
					CLEO [64] (5.4), Belle [57] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [65] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [65] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [61] (3.1)	2010	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 [66] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [67] (np), Belle [68] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [69,70] (6.4), BABAR [71] (2.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [72] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [68] (5.8)	2007	NC!
$Z_b(10610)^+$	10607.2±2.0	18.4±2.4	1^+	$\Upsilon(5S) \to \pi^-(\pi^+[b\bar{b}])$	Belle [73,74] (16)	2011	NC!
$Z_b(10650)^+$	10652.2±1.5	11.5±2.2	1^+	$\Upsilon(5S) \to \pi^-(\pi^+[b\bar{b}])$	Belle [73,74] (16)	2011	NC!
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [75,76] (2.0)	2010	NC!

Previous unsuccessful searches for h_b focused on what was considered the most easily detected production mechanism, $\Upsilon(3S) \to \pi^0 h_b(1P)$. In early 2011 BABAR presented marginal evidence for this transition at the 3σ level, at a mass near that expected for zero hyperfine splitting.

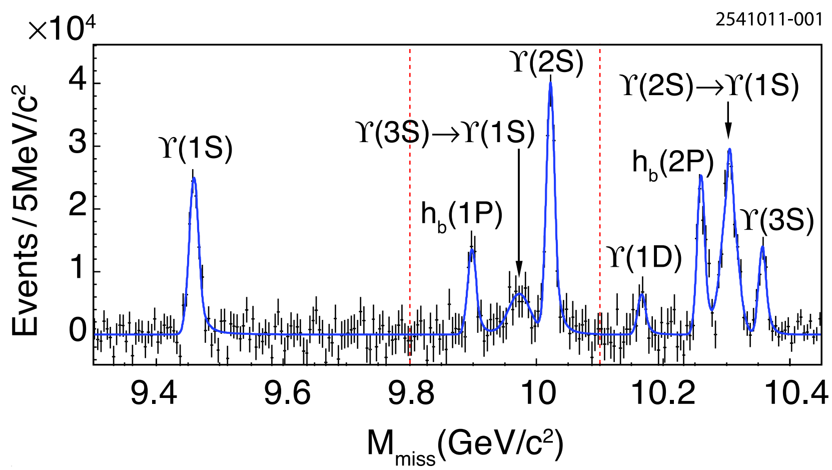

Figure 1: From Belle [31], the mass recoiling against $\pi^+\pi^-$ pairs, $M_{\rm miss}$, in e^+e^- collision data taken near the peak of the $\Upsilon(5S)$ (*points with error bars*). The smooth combinatoric and $K^0_S \to \pi^+\pi^-$ background contributions have already been subtracted. The fit to the various labeled signal contributions overlaid (*curve*). Adapted from [31] with kind permission, copyright (2011) The American Physical Society.

The Belle h_b discovery analysis [31] selects hadronic events and looks for peaks in the mass recoiling against $\pi^+\pi^-$ pairs, the spectrum for which, after subtraction of smooth combinatoric and $K^0_S \to \pi^+\pi^-$ 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 new CLEO result [77], 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 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).

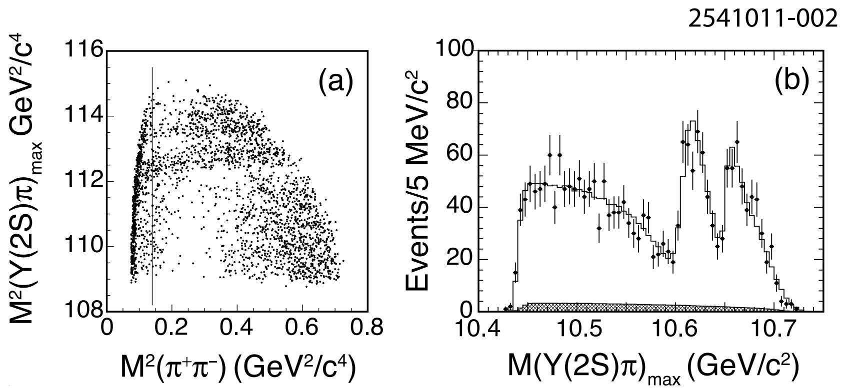

Figure 2: From Belle [74] e^+e^- collision data taken near the peak of the $\Upsilon(5S)$ for events with a $\pi^+\pi^-$-missing mass consistent with a $\Upsilon(nS)2$, (a) the maximum of the two possible single $\pi^\pm$-missing-mass-squared combinations vs. the $\pi^+\pi^-$-mass-squared; and (b) projection 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 [74] with kind permission, copyright (2011) The American Physical Society.

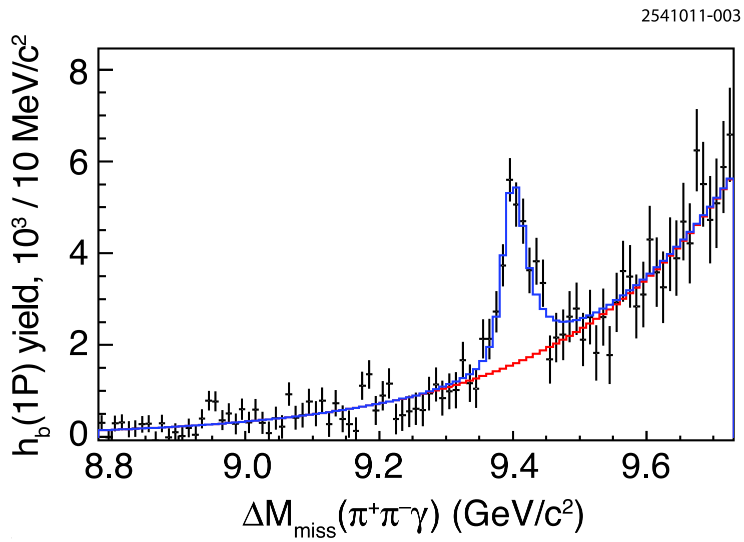

Figure 3: From Belle [30] e^+e^- collision data taken near the peak of the $\Upsilon(5S)$, the $h_b(1P)$ event yield vs. the mass recoiling against the $\pi^+\pi^-\gamma$ (corrected for misreconstructed $\pi^+\pi^-$), where the $h_b(1P)$ yield is obtained by fitting the mass recoiling against the $\pi^+\pi^-$ (*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.

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 do not appear 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. Angular analysis favors a $J^P = 1^+$ assignment for both Z_b^+ states, 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. The Z_b^+ cannot be simple mesons because they are charged and have $b\bar{b}$ content.

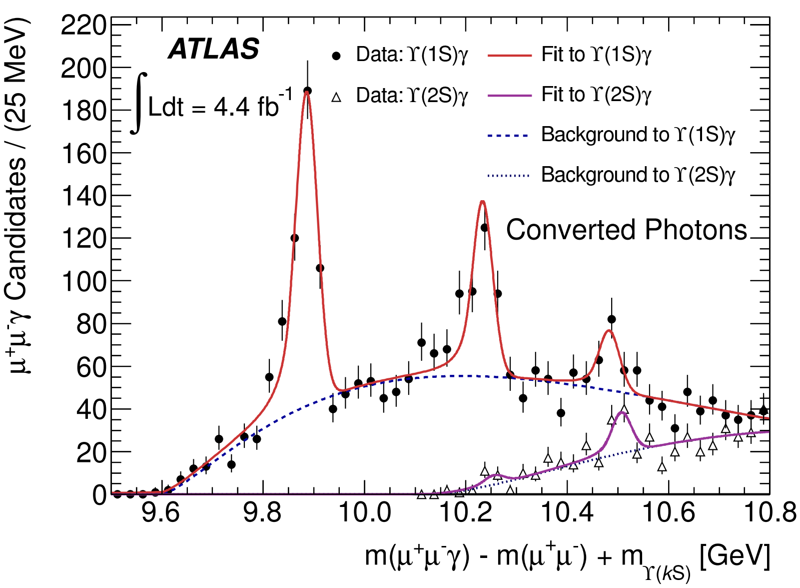

Figure 4: From ATLAS [35] *pp* collision data (*points with error bars*) taken at $\sqrt{s}$ = 7 TeV, the effective mass of $\chi_{bJ}(1P, 2P, 3P) \to \gamma\Upsilon(1S, 2S)$ candidates in which $\Upsilon(1S, 2S) \to \mu^+\mu^-$ and the photon is reconstructed as an e^+e^- conversion in the tracking 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.

The third Belle result to flow from these data is 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 spectrun, as shown in Fig. 3. A clear peak is observed, corresponding to the $\eta_b(1S)$. A fit is performed to extract the $\eta_b(1S)$ mass, and first measurements of its width and the branching fraction for $h_b(1P) \to \gamma\eta_b(1S)$ (the latter of which is $(49.8 \pm 6.8^{+10.9}_{-\ 5.2})\%$). The mass determination has comparable uncertainty to 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, as shown in Table 3.

Table 3: Measured $\eta_b(1S)$ masses and hyperfine splittings, by experiment and production mechanism.

$m(\eta_b)$	Δm_{hf}	Process	Ref. (χ^2/d.o.f.)
$9394.2^{+4.8}_{-4.9}\pm2.0$	$66.1^{+4.9}_{-4.8}\pm2.0$	$\Upsilon(nS)2 \to \gamma\eta_b$	BABAR [29]
$9388.9^{+3.1}_{-2.3}\pm2.7$	$71.4^{+2.3}_{-3.1}\pm2.7$	$\Upsilon(nS)3 \to \gamma\eta_b$	BABAR [27]
$9391.8\pm6.6\pm2.0$	$68.5\pm6.6\pm2.0$	$\Upsilon(nS)3 \to \gamma\eta_b$	CLEO [28]
9391.0 ± 2.8	69.3 ± 2.9	Above [7]	Avg[a] (0.6/2)
$9401.0\pm1.9^{+1.4}_{-2.4}$	$59.3\pm1.9^{+2.4}_{-1.4}$	$h_b(1P) \to \gamma\eta_b$	Belle [30]
9395.8 ± 3.0	64.5 ± 3.0	All	Avg[a] (6.1/3)

[a] An inverse-square-error-weighted average of the individual measurements appearing above, for which all statistical and systematic errors were combined in quadrature without accounting for any possible correlations between them. The uncertainty on this average is inflated by the multiplicative factor S if $S^2 \equiv \chi^2/\text{d.o.f.}>1$.

The $\chi_{bJ}(nP)$ states have recently been observed at the LHC by ATLAS [35] 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 mass in the χ_b region. Observation of all three J-merged peaks is seen at 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.

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