78. Spectroscopy of Mesons Containing Two Heavy Quarks

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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. Indeed, CLEO-c, BESIII, and the B-factories, later joined by ATLAS, CMS and LHCb, have made a series of groundbreaking observations. For an extensive presentation of the status of heavy quarkonium physics, the reader is referred to several reviews [1–7]. This note focuses on experimental developments in heavy quarkonium spectroscopy with very few theoretical comments. Possible theoretical interpretations of the states not predicted by the quark model are presented in the review "Heavy non-$q\bar{q}$ mesons." Note that in this review we follow the new naming scheme for hadrons (see the review "Naming scheme for hadrons" in the current edition).

This review covers states discovered since 2003, the year that marked the unexpected discovery of the $X(3872)$ [8]. The $X(3872)$, now called $\chi_{c1}(3872)$, was the first of the mesons containing two heavy quarks that could not be easily accommodated by the $q\bar{q}$ quark model. Its discovery was a watershed event in meson spectroscopy. 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. [9] and sort the states into three groups, namely states below (*cf.* Table 78.1), above (*cf.* Table 78.2), and near (*cf.* Table 78.3) the lowest open-flavor thresholds.

78.1 States Below Open-Flavor Threshold

Table 78.1 lists properties of recently observed heavy quarkonium states located below the lowest open-flavor thresholds. Those are expected to be (at least prominently) conventional quarkonia. The majority of charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) states were established prior to 2003.

78.1.1 *Charmonium*

The $h_c(1P)$ is the 1^1P_1 charmonium state, the singlet partner of the long-known χ_{cJ} triplet 1^3P_J. After being firmly established in 2005 through the process $\psi(2S) \to \pi^0 h_c(1P)$ [10], it has since been studied extensively by BESIII using large samples of $\psi(2S)$ decays. Exclusive hadronic decays of the $h_c(1P)$, strongly suppressed relative to the dominant radiative transition $h_c(1P) \to \gamma\eta_c(1S)$, were first observed in 2019 [11] and 2020 [12].

Belle reported an observation of the $\psi_2(1D)$ decaying to $\gamma\chi_{c1}$ with J^{PC} presumed to be 2^{--} [13]. This state is listed in Table 78.1 as $\psi_2(3823)$. Its existence was confirmed with high significance by BESIII [14]. While the negative C-parity is indeed established by its observed decay channel, the assignment of $J = 2$ was done by matching to the closest quark model state (1^3D_2) and requires experimental confirmation.

The 1^1D_2 state, or the $\eta_{c2}(1D)$, with a mass expected near 3820 MeV, has not yet been observed. Recently Belle performed a search in $B \to \eta_{c2}(1D)K(\pi)$ decays in the mass range 3795–3845 MeV and found no signal [15]. Thus, the $\eta_{c2}(1D)$ remains the only unobserved conventional charmonium state that does not have open-charm decays.

Table 78.1: 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 PDG21 weighted averages with statistical and systematic uncertainties added in quadrature. In the Production column, the state is always denoted by X. Ellipses (...) indicate inclusively selected event topologies, *i.e.*, additional particles not directly detected by experiment. A question mark (?) indicates an unmeasured value. The Discovery Year column gives the date of the first measurement cited. The Summary Table column indicates whether or not the state appears in the summary tables, usually requiring at least two independent experiments with significance of $>5\sigma$. Refer to the particle listings for references and further information.

PDG Name	Former Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$h_c(1P)$		3525.38 ± 0.11	0.7 ± 0.35	$0^-(1^{+-})$	$\psi(2S) \to \pi^0 X$	$\gamma\eta_c(1S)$	2004	YES
					$p\bar{p} \to X$	hadrons		
					$e^+e^- \to \pi\pi X$	(see listings)		
$\psi_2(3823)$	$X(3823)$	3823.7 ± 0.5	< 5.2	$0^-(2^{--})$	$B \to KX$	$\gamma\,\chi_{c1}(1P)$	2013	YES
					$e^+e^- \to \pi^+\pi^- X$	$\pi^+\pi^- J/\psi(1S)$		
B_c^+		6274.47 ± 0.32	stable	$0(0^-)$	$\bar{p}p \to X...$	$\pi^+ J/\psi(1S)$	2007	YES
					$pp \to X...$	(see listings)		
$B_c^+(2S)$		6871.2 ± 1.0	?	$0(0^-)$	$pp \to X...$	$B_c^+\pi^+\pi^-$	2014	YES
$\eta_b(1S)$		9398.7 ± 2.0	10^{+5}_{-4}	$0^+(0^{-+})$	$\Upsilon(2S,3S) \to \gamma X$	hadrons	2008	YES
					$h_b(1P,2P) \to \gamma X$	(see listings)		
$h_b(1P)$		9899.3 ± 0.8	?	$0^-(1^{+-})$	$\Upsilon(10860) \to \pi^+\pi^- X$	$\gamma\eta_b(1S)$	2011	YES
					$\Upsilon(3S) \to \pi^0 X$			
					$\Upsilon(4S) \to \eta X$			
					$Z_b(10610)^+ \to \pi^+ X$			
					$Z_b(10650)^+ \to \pi^+ X$			
$\eta_b(2S)$		$9999.0^{+4.5}_{-4.0}$	< 24	$0^+(0^{-+})$	$h_b(2P) \to \gamma X$	hadrons	2012	NO
$\Upsilon_2(1D)$		10163.7 ± 1.4	?	$0^-(2^{--})$	$\Upsilon(3S) \to \gamma\gamma X$	$\gamma\gamma\Upsilon(1S)$	2004	YES
					$\Upsilon(10860) \to \pi^+\pi^- X$	$\pi^+\pi^-\Upsilon(1S)$		
$h_b(2P)$		10259.8 ± 1.2	?	$0^-(1^{+-})$	$\Upsilon(10860) \to \pi^+\pi^- X$	$\gamma\eta_b(1S,2S)$	2011	YES
					$Z_b(10610)^+ \to \pi^+ X$			
					$Z_b(10650)^+ \to \pi^+ X$			
$\chi_{b1}(3P)$		10513.42 ± 0.67	?	$0^+(1^{++})$	$pp \to X...$	$\gamma\Upsilon(1S,2S,3S)$	2011	YES
$\chi_{b2}(3P)$		10524.02 ± 0.78	?	$0^+(2^{++})$	$pp \to X...$	$\gamma\Upsilon(3S)$	2011	YES

78.1.2 *Bottomonium*

The ground state of bottomonium, $\eta_b(1S)$, is well established. After the initial reports from BaBar in radiative decays of the $\Upsilon(3S)$ (observation) [16] and $\Upsilon(2S)$ (evidence) [17], Belle confirmed the existence of the $\eta_b(1S)$ with more than 5σ significance in radiative decays of the newly discovered $h_b(1P)$ [18, 19] and $h_b(2P)$ [18] (see next paragraph), as well as in $\Upsilon(2S)$ radiative decays [20]. Belle has also reported strong evidence for the $\eta_b(2S)$ [18], but it still needs confirmation at the 5σ level. Note that there are hints of tension in the $\eta_b(1S)$ mass as measured in radiative M1 and E1 transitions. In the M1 transition $\Upsilon(2S) \to \gamma\eta_b(1S)$ Belle measures a mass of $9394.8^{+2.7+4.5}_{-3.1-2.7}$ MeV/c^2 [20], while in the E1 transitions $h_b(1P,2P) \to \gamma\eta_b(1S)$ Belle measures $9402.4 \pm 1.5 \pm 1.8$ MeV/c^2 [18]. This tension may point to an incomplete understanding of the $\eta_b(1S)$ lineshape in different production mechanisms.

The $h_b(1P)$, the bottomonium counterpart of the $h_c(1P)$, and the next excited state, the $h_b(2P)$, were simultaneously discovered by Belle using dipion transitions from the $\Upsilon(10860)$ [21] (Fig. 78.1). The same analysis also showed the $\Upsilon_J(1D)$, the lowest-lying D-wave triplet of the $b\bar{b}$ system, but

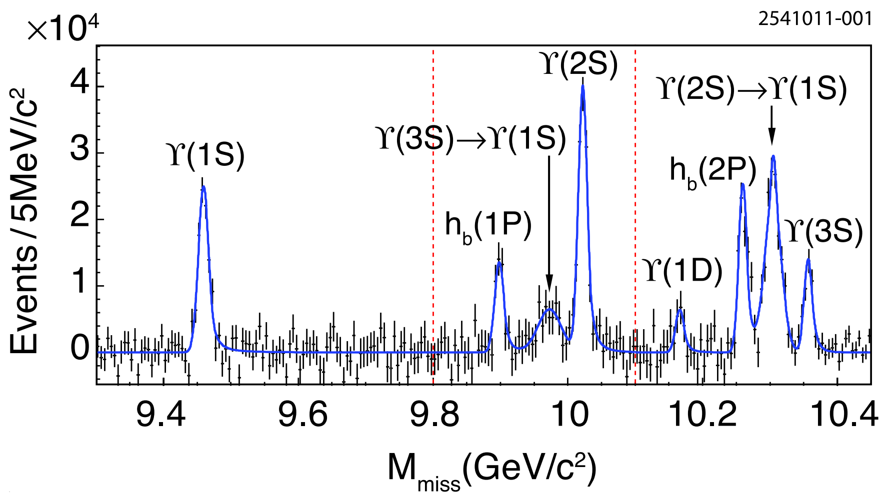

Figure 78.1: From Belle [21], the mass recoiling against $\pi^+\pi^-$ pairs, M_{miss}, in e^+e^- collision data taken near the peak of the $\Upsilon(10860)$ (*points with error bars*). The smooth combinatorial and $K^0_S \to \pi^+\pi^-$ background contributions have been subtracted. The fit to the various labeled signal contributions is overlaid (*curve*).

did not resolve the $J = 1, 2, 3$ components. The search for the $h_b(1P)$ was directly inspired by a CLEO result [22], which found a surprisingly copious production of $e^+e^- \to \pi^+\pi^- h_c(1P)$ as well as an indication that $\psi(4230) \to \pi^+\pi^- h_c(1P)$ occurs at a comparable rate with the signature mode $\psi(4230) \to \pi^+\pi^- J/\psi(1S)$. The presence of $\Upsilon(nS)$ peaks in Fig. 78.1 at rates two orders of magnitude larger than expected, 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 the $h_b(1P)$ 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 the $h_b(1P)$ in Ref. [23]). Belle later observed the transition $\Upsilon(4S) \to h_b(1P)\eta$ [19] and the corresponding 1P hyperfine splitting was also found to be compatible with zero at a similar precision level.

Just before Christmas 2011, ATLAS offered the world a beautiful gift, in the form of the discovery of the $\chi_b(3P)$ quarkonium state [24], observed by combining dimuons from $\Upsilon(1S)$ or $\Upsilon(2S)$ decays with photons emitted in the radiative $\chi_b(3P)$ decays (Fig. 78.2, bottom left panel). The new resonance, with a mass of $10\,530 \pm 5(\text{stat}) \pm 9(\text{syst})$ MeV, was soon confirmed by D0 [25]. Also LHCb observed the $\chi_b(3P)$ peak, using the full Run 1 event sample, corresponding to an integrated luminosity of 3 fb^{-1} [26] (Fig. 78.2, middle left panel). Finally, CMS used 80 fb^{-1} of 13 TeV pp collisions, collected in 2016 and 2017, to show two well-resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ peaks [27], separated by a mass difference of $10.60 \pm 0.64(\text{stat}) \pm 0.17(\text{syst})$ MeV (Fig. 78.2, top left panel). The remarkable precision of the individual mass measurements, with relative uncertainties as small as 50 ppm, shows that the LHC experiments can provide important results in the field of hadron spectroscopy, especially in the case of heavy particles, which require very high collision energies and large event samples.

78.1.3 B_c System

The $B_c^\pm$ family is quite special because these (charged) quarkonium states consist of two heavy quarks of different flavor. Among other interesting properties, this means that they cannot annihilate into gluons, the excited states only decaying to the pseudoscalar ground state, $B_c^\pm$, via electromagnetic and pionic transitions.

On the basis of an event sample collected in the Run 1 of the LHC, corresponding to an

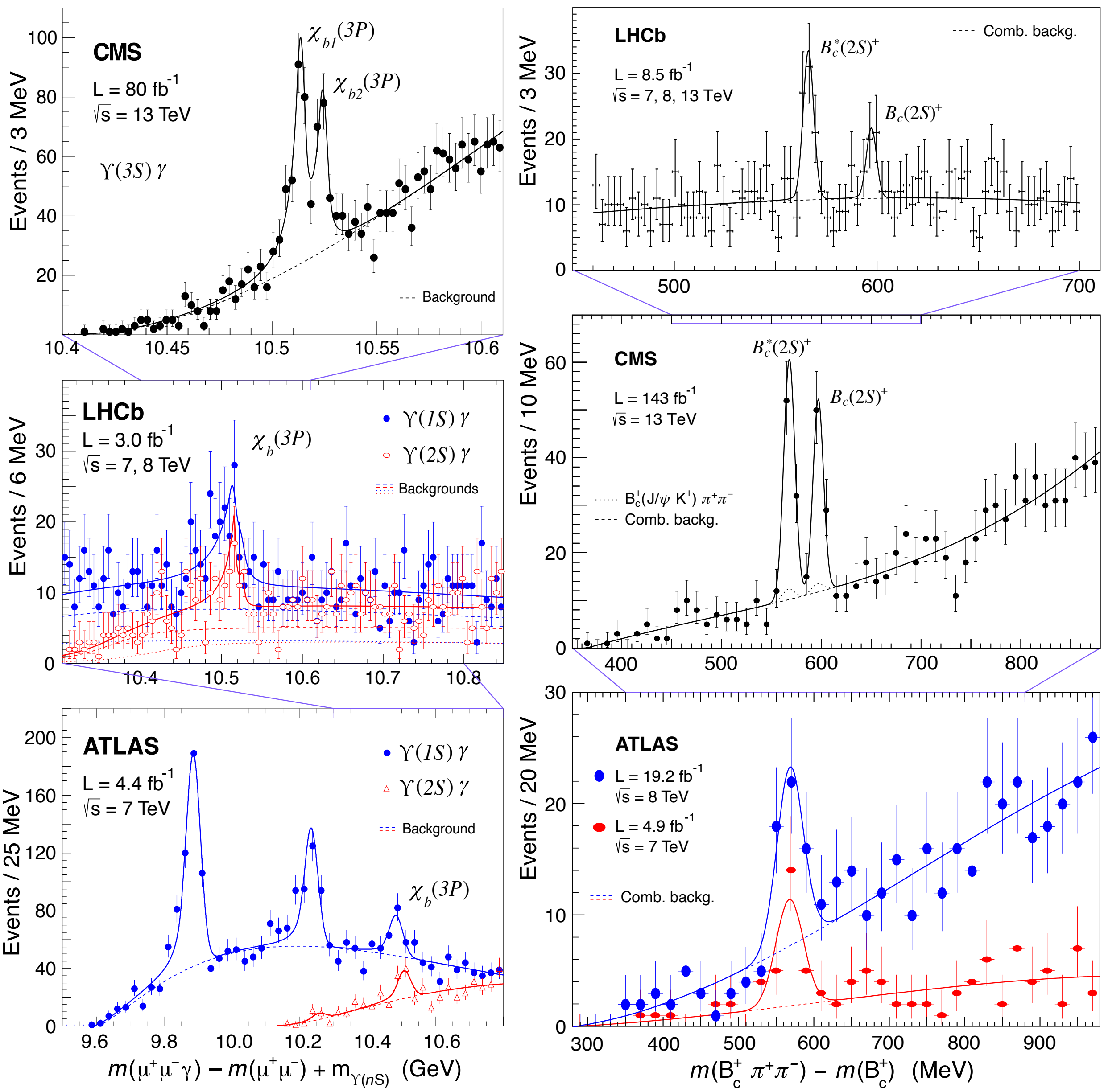

Figure 78.2: (Left Column) Invariant mass distributions measured by the ATLAS [24] (bottom), LHCb [26] (middle) and CMS [27] (top) experiments in their searches for the $\chi_b(3P)$ states through their radiative decays to one of the S-wave bottomonia. (Right Column) Invariant mass distributions measured by the ATLAS [28] (bottom), CMS [29] (middle) and LHCb [30] (top) experiments in their searches for $B_c^\pm$ excited states decaying to the $B_c^\pm$ ground state with the emission of two charged pions.

integrated luminosity of 24 fb^{-1}, adding the 7 and 8 TeV data, the ATLAS Collaboration observed a resonance in the $B_c^+\pi^+\pi^-$ invariant mass spectrum [28] (Fig. 78.2, bottom right panel). This peak, observed with a significance of 5.2 standard deviations and a mass of $6842 \pm 4(\text{stat}) \pm 5(\text{syst})$ MeV, was immediately recognized as the $B_c(2S)^\pm$ state, the first radial excitation in the $B_c^\pm$ family. Profiting from the much larger Run 2 event sample, collected in the 2015, 2016, 2017 and 2018 running periods and corresponding to 143 fb^{-1} of 13 TeV pp collisions, as well as from a measurement resolution of around 6 MeV, the CMS Collaboration could observe *two* well-resolved peaks, separated by $29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV [29] (Fig. 78.2, middle right panel). The existence of two peaks, rather than a single one, is established with a significance of 6.5 standard deviations. The "right peak" has a mass of $6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)$ MeV, where the last term is the uncertainty in the B_c^+ mass, and is identified as the $B_c(2S)^\pm$ state, which decays directly to the $B_c^\pm$, emitting two (easy to detect) pions. The CMS observation, reported a couple of months after the end of the LHC Run 2, was soon followed by the corresponding LHCb result [30] (Fig. 78.2, top right panel), which confirmed the existence of the two states and reported a second measurement of the $B_c(2S)^\pm$ mass, $6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)$ MeV.

The "left peak" is interpreted as being the $B_c^*(2S)^\pm$ signal. It is observed at a mass lower than the real value because the experiments are unable to detect the low-energy photon emitted in the decay chain, $B_c^*(2S)^\pm \to B_c^{*\pm}\,\pi^+\pi^-$ followed by $B_c^{*\pm} \to B_c^\pm\,\gamma$ (Fig. 78.3). Its energy, expected to be in the range 40–80 MeV, leads to a very small probability that the photon converts into an e^+e^- pair and the two electrons are reconstructed. The relative ordering of the two peaks is based on a generally-agreed assumption: the $M(B_c^{*\pm}) - M(B_c^\pm)$ mass difference is larger than the $M(B_c^*(2S)^\pm) - M(B_c(2S)^\pm)$ difference. Naturally, these observations provide evidence for the existence of the $B_c^*(1S)^\pm$ state. They also provide measurements of two interesting mass differences, between the masses of the pseudoscalar mesons, $M(B_c(2S)^\pm) - M(B_c(1S)^\pm) = 596.1$ MeV, and of the vector mesons, $M(B_c^*(2S)^\pm) - M(B_c^*(1S)^\pm) = 567.0$ MeV (Fig. 78.3).

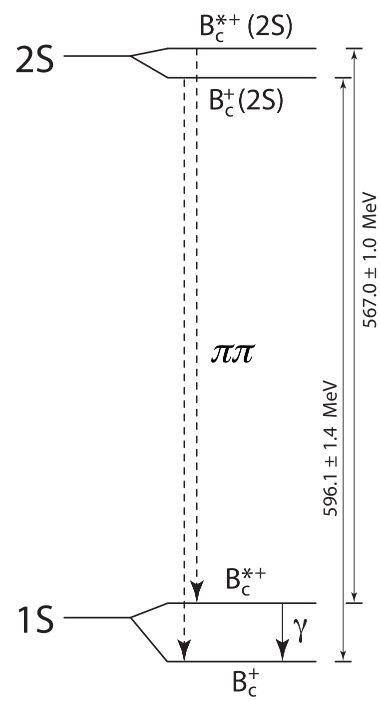

Figure 78.3: Diagram showing the decays mentioned in the text.

78.2 States Above Open-Flavor Threshold

Many states have been discovered both above and near the lowest open-flavor thresholds. They are displayed in Tables 78.2 and 78.3, respectively. With the exception of the $\psi_3(3842)$ and the tensor state located at 3930 MeV (now called $\chi_{c2}(3930)$), which have properties consistent with those expected for the $\psi_3(1^3D_3)$ and $\chi_{c2}(2^3P_2)$, respectively, none of these states can easily be assigned a place in the quark model spectrum of the charmonium or bottomonium families. At the same time, these states also have no universally accepted unconventional interpretation.

78.2.1 *Charmonium*

Using proton-proton collisions, LHCb observed a narrow state, the $\psi_3(3842)$ resonance, in the decay modes $\psi_3(3842) \to D^0\bar{D}^0$ and D^+D^- [31]. The mass and width of this state are measured to be $3842.71 \pm 0.16 \pm 0.12$ MeV and $2.79 \pm 0.51 \pm 0.35$ MeV, respectively. The observed mass and narrow width are consistent with the interpretation of the new state as the unobserved spin-3 $\psi_3(1^3D_3)$ charmonium. Accordingly, the state got the name $\psi_3(3842)$ in the listings, with the remark that the quantum numbers were fixed from the quark model and need to be confirmed.

The $\chi_{c2}(3930)$, which is a natural candidate for the $\chi_{c2}(2^3P_2)$ quark model state, was originally seen by Belle [32] and later confirmed by BaBar [33] in the $\gamma\gamma$ process $e^+e^- \to e^+e^-D\bar{D}$. This interpretation was strengthened by the more recent LHCb observation of the $\chi_{c2}(3930)$ alongside the $\psi_3(3842)$ in proton-proton collisions [31].

Unlike the $\chi_{c2}(2^3P_2)$, the identification of the $\chi_{c0}(2^3P_0)$ quark model state remains controversial. The original candidate was the $\chi_{c0}(3915)$, discovered by Belle in the $\gamma\gamma$ process $e^+e^- \to e^+e^-\omega J/\psi(1S)$ [34]. In a subsequent measurement by BaBar, its quantum numbers were determined to be $J^{PC} = 0^{++}$ [35]. However, its identification as the $\chi_{c0}(2^3P_0)$ quark model state was soon challenged [36, 37]. In addition, it was pointed out in Ref. [38] that if the assumption of helicity-2 dominance is abandoned and, instead, one allows for a sizeable helicity-0 component, a $J^{PC} = 2^{++}$ assignment is possible. This could imply that it is the same as the $\chi_{c2}(3930)$—but to explain the large helicity-0 component a sizable portion of non-$q\bar{q}$ is necessary [38]. A more recent LHCb amplitude analysis of the process $B^+ \to D^+D^-K^+$ finds distinct 0^{++} and 2^{++} components decaying to D^+D^- [39], which are currently identified in the listings as the $\chi_{c0}(3915)$ and $\chi_{c2}(3930)$, respectively.

An alternative candidate for the $\chi_{c0}(2^3P_0)$ (here referred to as the $\chi_{c0}(3860)$) was reported in Ref. [40] with properties more consistent with expectation: its mass is close to the potential model expectations, it decays to $D\bar{D}$, and the preferred quantum numbers are $J^{PC} = 0^{++}$ (this hypothesis is favored over the 2^{++} one with a 2.5σ significance).

In the excited vector charmonium spectrum, the $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ are prominent in the inclusive e^+e^- hadronic cross section and are naturally identified as the 3^3S_1, 2^3D_1, and 4^3S_1 $c\bar{c}$ quark model states, respectively. In addition to these long-established states, however, another set of mesons has been found as peaks in exclusive e^+e^- cross sections. Unlike conventional vector charmonia, they do not appear in the inclusive hadronic cross section and they apparently do not decay to $D\bar{D}$. The PDG summary table currently lists the $\psi(4230)$, $\psi(4360)$, and $\psi(4660)$ within this category. The first of these to be discovered was originally known as the $Y(4260)$ (now the $\psi(4230)$), seen by BaBar [41] and Belle [42, 43] in $e^+e^- \to \pi^+\pi^-J/\psi(1S)$ using initial state radiation. In a more recent high-statistics scan of $e^+e^- \to \pi^+\pi^-J/\psi(1S)$, BESIII demonstrated that the lineshape in this mass range is highly non-trivial [44]. The latter observation was interpreted by the authors as the presence of two states. However, this lineshape is also consistent with other possible interpretations, such as one assuming a molecular structure for the $\psi(4230)$ [45]. The data of Ref. [44] also called for a significant downward shift of the mass of what was originally called the $Y(4260)$, making it consistent with peaks in other exclusive cross sections, such as $h_c(1P)\pi\pi$ [46]. We thus merged the original $Y(4260)$ (or, more formally, the $\psi(4260)$) with the $\psi(4230)$ in the listings.

BESIII observed the $\chi_{c1}(3872)$, also known as $X(3872)$, in $e^+e^- \to \gamma\chi_{c1}(3872)$ in the $\psi(4230)$ mass range [47], which could allow for additional insight into the structure of both states (see the review on heavy non-$q\bar{q}$ mesons). BESIII also performed a recent study of the process $e^+e^- \to$

$\pi^+\pi^-\psi(2S)$ and found evidence for a lower mass state, possibly the $\psi(4230)$, in addition to the more dominant $\psi(4360)$ [48].

Note that the data of Ref. [44] does not show any indication of the $Y(4008)$ reported by Belle; the data in this region can either be fit with a non-resonant background component or a much wider resonance at lower mass. Also the analysis of the $Y(4008)$ region in Ref. [49] indicates a wide resonance.

Another interesting question is whether a heavier $\pi^+\pi^-\psi(2S)$ state, the $\psi(4660)$, discovered by Belle [50, 51] and confirmed by BaBar [52], is identical to the $\Lambda_c^+\bar{\Lambda}_c^-$ resonance observed by Belle with a nearby mass and width [53]. Most probably it is, the $\Lambda_c^+\bar{\Lambda}_c^-$ being one more decay mode of the $\psi(4660)$ (see the review on heavy non-$q\bar{q}$ mesons for more detail). Note that this is the interpretation adopted in the particle listings. In addition, Belle reported the first observation of a vector charmonium-like state decaying to $D_s^+D_{s1}(2536)$ with a significance of 5.9σ [54]. Its measured mass and width are $4625.9^{+6.2}_{-6.0}\pm0.4$ MeV and $49.8^{+13.9}_{-11.5}\pm4.0$ MeV, respectively, consistent with those of the $\psi(4660)$. Therefore, $D_s^+D_{s1}(2536)$ appears as an additional decay mode of the $\psi(4660)$ in the listings.

A series of isovector states containing $c\bar{c}$ have been found in B decays to $K\pi(c\bar{c})$, where the isovector state decays to $\pi(c\bar{c})$ and $(c\bar{c})$ stands for $J/\psi(1S)$, $\psi(2S)$, or χ_{c1}. They are manifestly non-$q\bar{q}$ and their discovery implied an expansion of the meson naming scheme. The $Z_c(4430)$, decaying to $\pi\psi(2S)$, is the most well established. Based on a full amplitude analysis of $B^0 \to K^+\pi^-\psi(2S)$ decays, Belle determined the spin-parity of the $Z_c(4430)$ to be $J^P = 1^+$ [55]. From their study of $B^0 \to K^+\pi^-J/\psi(1S)$ decays, Belle also found evidence for the decay mode $Z_c(4430) \to \pi J/\psi(1S)$ [56], which has an order of magnitude lower branching fraction than the discovery mode $Z_c(4430) \to \pi\psi(2S)$. In the same analysis, Belle reported evidence for one more charged state, dubbed $Z_c(4200)$, decaying to $\pi J/\psi(1S)$. The existence of the $Z_c(4430)$ in $\pi\psi(2S)$, as well as its quantum number assignments, were confirmed by LHCb [57] with a much larger data sample, leading to improved mass and width values, consistent with earlier measurements; the experiment even reports a resonant behavior of the $Z_c(4430)$ amplitude. The $Z_c(4430)$ was not confirmed (or excluded) by BaBar [58].

Belle also reported an observation of two charged states decaying to $\pi\chi_{c1}$ in an analysis of $B^0 \to K^+\pi^-\chi_{c1}$ decays [59]. These were originally called the $Z_1(4050)^\pm$ and the $Z_2(4250)^\pm$, but are referred to in Table 78.2 as $X(4050)^\pm$ and $X(4250)^\pm$. These states were not confirmed by BaBar [60]. Belle observes signals with 5.0σ significance for both the $Z_1(4050)^\pm$ and $Z_2(4250)^\pm$, whereas BABAR reports 1.1σ and 2.0σ effects, respectively, setting upper limits that are not inconsistent with Belle's measured rates. The situation remains unresolved.

The decay $B^+ \to K^+\phi J/\psi(1S)$ appears to be especially rich in resonant substructure. The $Y(4140)$ (now the $\chi_{c1}(4140)$), decaying to $\phi J/\psi(1S)$, was first observed in 2008 by CDF [61,62], and confirmed by D0 and CMS [63, 64]. However, a second structure, the $Y(4274)$ (now the $\chi_{c1}(4274)$), could not be established unambiguously. Neither of the two states was seen in B decays at Belle [65], LHCb [66] and BaBar [67], or in $\gamma\gamma$ collisions at Belle [68]. The real breakthrough happened when LHCb performed a full amplitude analysis of $B^+ \to K^+\phi J/\psi(1S)$ with $J/\psi(1S) \to \mu^+\mu^-$, $\phi \to K^+K^-$ decays and showed that the data cannot be described in a model that contains only excited kaon states decaying into $K^+\phi$ [69, 70]. They observe two 1^{++} states with masses close to those originally reported by CDF (the $\chi_{c1}(4140)$ and $\chi_{c1}(4274)$), but the width of the one at 4140 MeV is much larger. In addition, they find two significant 0^{++} structures at 4500 and 4700 MeV (the $\chi_{c0}(4500)$ and $\chi_{c0}(4700)$).

78.2.2 *Bottomonium*

Belle reported a new measurement of the $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ cross sections at energies from 10.52 to 11.02 GeV [71]. They observed, with a 5.2σ significance, a new structure

Table 78.2: As in Table 78.1, but for new states above the first open-flavor thresholds in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass.

PDG Name	Former Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\psi_3(3842)$		3842.71 ± 0.20	2.79 ± 0.62	$0^-(3^{--})^*$	$pp \to X...$	$D\bar{D}$	2019	YES
$\chi_{c0}(3860)$		3862^{+48}_{-35}	201^{+177}_{-106}	$0^+(0^{++})$	$e^+e^- \to J/\psi(1S)X$	$D\bar{D}$	2017	NO
$\chi_{c0}(3915)$	$X(3915)$, $Y(3940)$	3921.7 ± 1.8	18.8 ± 3.5	$0^+(0/2^{++})$	$B \to KX$ $e^+e^- \to e^+e^-X$	$\omega J/\psi(1S)$ $D\bar{D}$	2004	YES
$\chi_{c2}(3930)$	$\chi_{c2}(2P)$, $Z(3930)$	3922.5 ± 1.0	35.2 ± 2.2	$0^+(2^{++})$	$e^+e^- \to e^+e^-X$	$D\bar{D}$	2005	YES
$X(3940)$		3942^{+9}_{-8}	37^{+27}_{-17}	$?^?(?^{??})$	$e^+e^- \to J/\psi(1S)X$	$D\bar{D}^*$	2007	NO
$X(4050)^\pm$	$Z_1(4050)$	4051^{+24}_{-43}	82^{+51}_{-28}	$1^-(?^{?+})$	$\bar{B}^0 \to K^-X$	$\pi^+\chi_{c1}(1P)$	2008	NO
$X(4055)^\pm$	$Z_c(4055)$	4054 ± 3	45 ± 13	$1^+(?^{?-})$	$e^+e^- \to \pi^-X$	$\pi^+\psi(2S)$	2015	NO
$X(4100)^\pm$		4096^{+27}_{-30}	152^{+83}_{-68}	$1^-(?^{??})$	$\bar{B}^0 \to K^-X$	$\pi^+\eta_c(1S)$	2018	NO
$\chi_{c1}(4140)$	$Y(4140)$	4146.5 ± 3.0	19^{+7}_{-5}	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2009	YES
$X(4160)$		4156^{+29}_{-25}	139^{+113}_{-65}	$?^?(?^{??})$	$e^+e^- \to J/\psi(1S)X$	$D^*\bar{D}^*$	2007	NO
$Z_c(4200)$		4196^{+35}_{-32}	370^{+99}_{-149}	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$J/\psi(1S)\pi^+$	2014	NO
$\psi(4230)$	$Y(4230)$ $Y(4260)$	4222.7 ± 2.6	49 ± 8	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-J/\psi(1S)$ $\omega\chi_{c0}(1P)$ $\pi^+\pi^-h_c(1P)$ (see listings)	2015	YES
$R_{c0}(4240)$	$Z_c(4240)$	4239^{+48}_{-21}	220^{+118}_{-88}	$1^+(0^{--})$	$\bar{B}^0 \to K^-X$	$\pi^+\psi(2S)$	2014	NO
$X(4250)^\pm$	$Z_2(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$1^-(?^{?+})$	$\bar{B}^0 \to K^-X$	$\pi^+\chi_{c1}(1P)$	2008	NO
$\chi_{c1}(4274)$	$Y(4274)$	4286^{+8}_{-9}	51 ± 7	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2011	YES
$X(4350)$		$4350.6^{+4.7}_{-5.1}$	13^{+18}_{-10}	$0^+(?^{?+})$	$e^+e^- \to e^+e^-X$	$\phi J/\psi(1S)$	2009	NO
$\psi(4360)$	$Y(4360)$	4372 ± 9	115 ± 13	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2S)$ $\pi^+\pi^-J/\psi(1S)$	2007	YES
$Z_c(4430)$		4478^{+15}_{-18}	181 ± 31	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$\pi^+\psi(2S)$ $\pi^+J/\psi(1S)$	2007	YES
$\chi_{c0}(4500)$	$X(4500)$	4474 ± 4	77^{+12}_{-10}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2017	NO
$X(4630)$		4626^{+24}_{-111}	174^{+137}_{-78}	$0^+(?^{?+})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2021	NO
$\psi(4660)$	$Y(4660)$, $X(4630)$	4630 ± 6	72^{+14}_{-12}	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2S)$ $\Lambda_c^+\bar{\Lambda}_c^-$ $D_s^+D_{s1}(2536)$	2007	YES
$\chi_{c1}(4685)$		4684^{+15}_{-17}	126^{+40}_{-44}	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2021	NO
$\chi_{c0}(4700)$	$X(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi(1S)$	2017	NO
$\Upsilon(10753)$		$10752.7^{+5.9}_{-6.0}$	36^{+18}_{-12}	$?^?(1^{--})$	$e^+e^- \to X$	$\pi\pi\Upsilon(1S,2S,3S)$	2019	NO
$\Upsilon(10860)$	$\Upsilon(5S)$	$10885.2^{+2.6}_{-1.6}$	37 ± 4	$0^-(1^{--})$	$e^+e^- \to X$	$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi)$ $\pi\pi\Upsilon(1S,2S,3S)$ $\pi^+\pi^-h_b(1P,2P)$ $\eta\Upsilon(1S,2S)$ $\pi^+\pi^-\Upsilon(1D)$ (see listings)	1985	YES
$\Upsilon(11020)$	$\Upsilon(6S)$	11000 ± 4	24^{+8}_{-6}	$0^-(1^{--})$	$e^+e^- \to X$	$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi)$ $\pi\pi\Upsilon(1S,2S,3S)$ $\pi^+\pi^-h_b(1P,2P)$ (see listings)	1985	YES

*Quantum numbers fixed from the quark model and need confirmation.

in the energy dependence of the cross sections. If described by a Breit–Wigner function, its mass and width are $10752.7 \pm 5.9^{+0.7}_{-1.1}$ MeV and $35.5^{+17.6+3.9}_{-11.3-3.3}$ MeV, respectively. The new structure could have a resonant origin and correspond to the not yet observed $\Upsilon(3D)$ state, provided $S-D$ mixing is enhanced, or an exotic state, e.g., a compact tetraquark or hadrobottomonium. It could also be a non-resonant effect due to rescattering.

We no longer mention a hypothetical $Y_b(10888)$ state since a new analysis of the $\Upsilon(10860)$ energy range does not show evidence for an additional state with a mass different from that of the $\Upsilon(10860)$ [72]. After the mass of the $\eta_b(1S)$ was shifted upwards by about 10 MeV based on the Belle measurements [18,19], all of the bottomonium states mentioned above fit into their respective spectroscopies, roughly where expected. An independent experimental confirmation of the shifted masses came from the Belle observation of $\Upsilon(4S) \to \eta h_b(1P)$ decays [19]. This process turns out to be the strongest observed transition of the $\Upsilon(4S)$ to lower bottomonium states.

78.3 States Near Open-Flavor Threshold

A number of states, listed in Table 78.3, appear near open-flavor thresholds, which is likely an important factor in their theoretical interpretation [73].

78.3.1 *Charmonium*

The $\chi_{c1}(3872)$, also known as $X(3872)$, is widely studied and seen in many transitions — see Table 78.3. Yet its interpretation remains unsettled (see the heavy non-$q\bar{q}$ review). Its unique experimental features include: it has $J^{PC} = 1^{++}$ [74, 75], yet it is too light to be the $\chi_{c1}(2^3P_1)$ quark model state; its mass is within 200 keV of the $D^0\bar{D}^{0*}$ threshold; it shows substantial isospin-breaking in its decays to $\rho J/\psi(1S)$ and $\pi^0\chi_{c1}$; and it is extremely narrow. Using a large sample of inclusively produced $\chi_{c1}(3872)$ decaying to $\pi^+\pi^- J/\psi(1S)$, LHCb recently determined the decay width of the $\chi_{c1}(3872)$ under two different assumptions [76]. Assuming a Flatté-inspired line shape and exploiting the strong coupling of the $\chi_{c1}(3872)$ to $D^0\bar{D}^{*0}$, LHCb performed the first exploration of the pole structure of the $\chi_{c1}(3872)$, finding a FWHM of $0.22^{+0.06+0.25}_{-0.08-0.17}$ MeV. On the other hand, assuming a Breit–Wigner line shape, its width was found to be $1.39 \pm 0.24 \pm 0.10$ MeV. While the former analysis has a more firm theoretical foundation, the LHCb detector resolution did not allow for a distinction between the different line shapes.

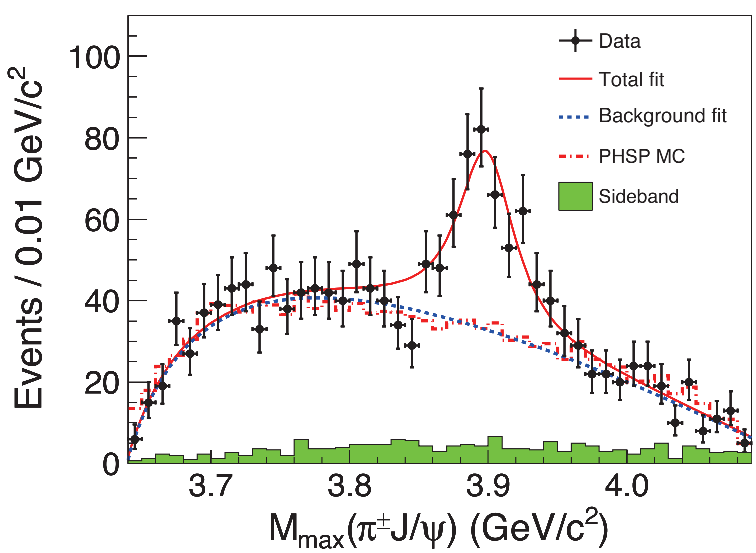

Figure 78.4: The $\pi^\pm J/\psi(1S)$ invariant mass distribution from BESIII [78] e^+e^- collision data taken at a center-of-mass energy near 4260 MeV.

In addition to the Z_c states found in B decays, discussed above, several isovector states with masses near $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds appear to be unique to e^+e^- annihilation. In 2013, a state named $Z_c(3900)$ was unearthed in the charmonium region at BESIII [78] and Belle [43] in the process $e^+e^- \to \pi^\mp Z_c(3900)^\pm$ with $Z_c(3900)^\pm \to \pi^\pm J/\psi(1S)$. The corresponding spectrum from BESIII

Table 78.3: As in Table 78.1, but for new states near the first open-flavor thresholds in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass. Updated from Ref. [77] with kind permission, copyright (2011), Springer, and from Ref. [9] with kind permission from the authors.

PDG Name	Former Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\chi_{c1}(3872)$	$X(3872)$	3871.65±0.06	1.19 ± 0.21	$0^+(1^{++})$	$B \to KX$ $p\bar{p} \to X...$ $pp \to X...$ $e^+e^- \to \gamma X$	$\pi^+\pi^- J/\psi(1S)$ $3\pi J/\psi(1S)$ $D^{*0}\bar{D}^0$ $\gamma J/\psi(1S)$ $\gamma\psi(2S)$ $\pi^0\chi_{c1}(1P)$	2003	YES
$Z_c(3900)$		3887.1 ± 2.6	28.4 ± 2.6	$1^+(1^{+-})$	$\psi(4230) \to \pi^- X$ $\psi(4230) \to \pi^0 X$	$\pi^+ J/\psi(1S)$ $\pi^0 J/\psi(1S)$ $(D\bar{D}^*)^+$ $(D\bar{D}^*)^0$	2013	YES
$X(4020)$	$Z_c(4020)$	4024.1 ± 1.9	13 ± 5	$1^+(?^{?-})$	$\psi(4230, 4360) \to \pi^- X$ $\psi(4230, 4360) \to \pi^0 X$	$\pi^+ h_c$ $\pi^0 h_c$ $(D^*\bar{D}^*)^+$ $(D^*\bar{D}^*)^0$	2013	YES
$Z_b(10610)$		10607.2 ± 2.0	18.4 ± 2.4	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$ $\Upsilon(10860) \to \pi^0 X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^0\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B\bar{B}^*)^+$	2011	YES
$Z_b(10650)$		10652.2 ± 1.5	11.5 ± 2.2	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B^*\bar{B}^*)^+$	2011	YES

is shown in Fig. 78.4. An analysis of CLEO data [79] confirmed this finding and also provided evidence for a neutral partner. A nearby signal was also seen in the $D\bar{D}^*$ channel [80] whose quantum numbers were fixed to 1^{+-}. BESIII reported its neutral partner in both $J/\psi(1S)\pi^0$ [81] and $D\bar{D}^*$ [82] decay modes. The masses extracted from these experiments in different decay modes have differences reaching up to 2σ. However, since the extraction of the mass and width parameters 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 in Table 78.3 both structures appear under the name $Z_c(3900)$. BESIII also reported an observation of another charged state, the $X(4020)^\pm$ (originally called $Z_c(4020)^\pm$), in two decay modes: $h_c\pi^\pm$ [83] and $(D^*\bar{D}^*)^\pm$ [84]. The neutral partners have also been observed by BESIII in the $h_c\pi^0$ [85] and $(D^*\bar{D}^*)^0$ [86] final states. The Z_c states show some remarkable similarities to the Z_b states (discussed below), e.g. they decay dominantly to $D^{(*)}\bar{D}^*$ channels. However, current analyses suggest that the mass of the $Z_c(3900)$ might be somewhat above the $D\bar{D}^*$ threshold. If confirmed, this feature would challenge a possible $D\bar{D}^*$–molecular interpretation with S-wave interactions only — prominent D-waves can shift molecular poles above threshold (see the discussion in Sec. 78.3.2). Finally, 3.5σ evidence for one more charged charmonium-like state at 4055 MeV decaying into $\psi(2S)\pi^\pm$ was reported by Belle in their analysis of the process $e^+e^- \to \psi(2S)\pi^+\pi^-$ [51]. This state was confirmed by BESIII, although there appears to be complications in the Dalitz plot requiring further investigation [48].

78.3.2 *Bottomonium*

New results on the η_b, h_b, and Z_b mostly come from Belle [18, 19, 21, 23, 72, 87–93], all from analyses of 121.4 fb^{-1} of e^+e^- collision data collected near the peak of the $\Upsilon(10860)$ resonance, as well as from an additional 25 fb^{-1} of data collected during the scans of the c.m. energy range 10.63–11.05 GeV. The η_b, h_b, and Z_b appear in the 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 $h_b(1P) \to \gamma\eta_b$.

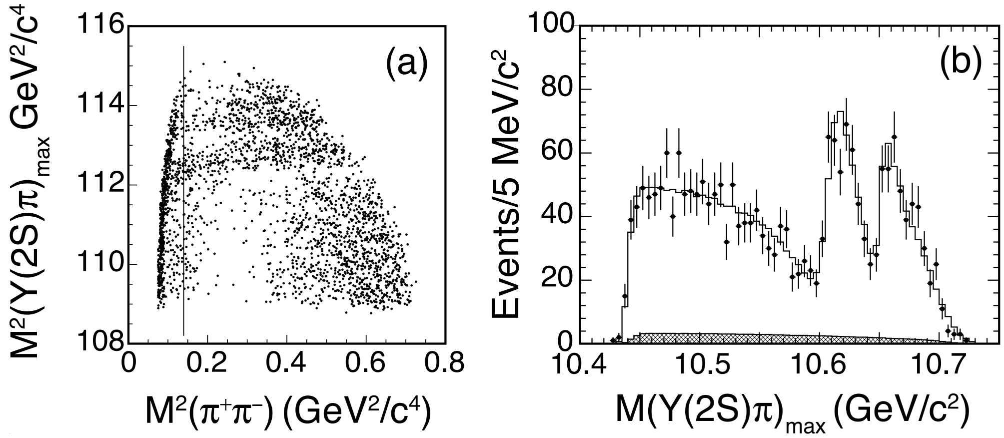

Figure 78.5: From Belle [87] e^+e^- collision data taken near the peak of the $\Upsilon(10860)$ for events with a $\pi^+\pi^-$-missing mass consistent with an $\Upsilon(2S) \to \mu^+\mu^-$, (a) the maximum of the two possible single $\pi^\pm$-missing-mass-squared combinations vs. the $\pi^+\pi^-$-mass-squared; 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 the amplitude analysis. The hatched histogram in (b) corresponds to the combinatorial background. The two horizontal stripes in (a) and two peaks in (b) correspond to the two Z_b states.

Belle soon noticed that, for events in the peaks of Fig. 78.1, there seemed to be two intermediate charged states, the $Z_b(10610)$ and the $Z_b(10650)$. For example, Fig. 78.5 shows a Dalitz plot for events restricted to the $\Upsilon(2S)$ region of $\pi^+\pi^-$ recoil mass, with $\Upsilon(2S) \to \mu^+\mu^-$ [87]. The two bands observed in the maximum of the two $M[\pi^\pm\Upsilon(2S)]^2$ values also appear in the $\Upsilon(1S)$, $\Upsilon(3S)$, $h_b(1P)$, and $h_b(2P)$ samples. 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 [88], 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. While the two masses of the Z_b states as extracted from Breit–Wigner fits for the various channels are just a few MeV above the $B^*\bar{B}$ and $B^*\bar{B}^*$ thresholds, more refined analyses using only S-waves find pole locations right below the corresponding thresholds either on the physical [94] or the unphysical [95] sheet. Once D-waves are included, the pole of the $Z_b(10650)$ moves above the $B^*\bar{B}^*$ threshold [96]. Regardless of their proximity to the corresponding thresholds, both states predominantly decay into these open-flavor channels [90, 97] with branching fractions that exceed 80% and 70%, respectively, at 90% CL. This feature provides strong evidence for their molecular nature.

78.4 Concluding Remarks

The discovery of the $\chi_{c1}(3872)$ (also known as the $X(3872)$) in 2003 ushered in an era of tremendous progress in experimental heavy quark meson spectroscopy. As shown in Tables 78.1 to 78.3, more than 40 new states have been reported during this period, many of which were unanticipated. While the states below open-flavor thresholds (Table 78.1) appear to be well-explained by the conventional $q\bar{q}$ quark model, a thorough understanding of the suite of states above (Table 78.2) and near (Table 78.3) open-flavor thresholds remains elusive. After nearly two decades, experimental progress remains rapid with the continuation of BESIII, the commencement of the Belle II program, and the imminent accumulation of additional data at the LHC.

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References

[1] N. Brambilla *et al.*, Phys. Rept. **873**, 1 (2020), [arXiv:1907.07583].

[2] Y.-R. Liu *et al.*, Prog. Part. Nucl. Phys. **107**, 237 (2019), [arXiv:1903.11976].

[3] S. L. Olsen, T. Skwarnicki and D. Zieminska, Rev. Mod. Phys. **90**, 1, 015003 (2018), [arXiv:1708.04012].

[4] A. Ali, J. S. Lange and S. Stone, Prog. Part. Nucl. Phys. **97**, 123 (2017), [arXiv:1706.00610].

[5] F.-K. Guo *et al.*, Rev. Mod. Phys. **90**, 1, 015004 (2018), [arXiv:1705.00141].

[6] R. F. Lebed, R. E. Mitchell and E. S. Swanson, Prog. Part. Nucl. Phys. **93**, 143 (2017), [arXiv:1610.04528].

[7] A. E. Bondar, R. V. Mizuk and M. B. Voloshin, Mod. Phys. Lett. A **32**, 04, 1750025 (2017), [arXiv:1610.01102].

[8] S. K. Choi *et al.* (Belle), Phys. Rev. Lett. **91**, 262001 (2003), [hep-ex/0309032].

[9] N. Brambilla *et al.*, Eur. Phys. J. **C74**, 10, 2981 (2014), [arXiv:1404.3723].

[10] J. L. Rosner *et al.* (CLEO), Phys. Rev. Lett. **95**, 102003 (2005), [hep-ex/0505073].

[11] M. Ablikim *et al.* (BESIII), Phys. Rev. D **99**, 7, 072008 (2019), [arXiv:1810.12023].

[12] M. Ablikim *et al.* (BESIII), Phys. Rev. D **102**, 112007 (2020), [arXiv:2010.12092].

[13] V. Bhardwaj *et al.* (Belle), Phys. Rev. Lett. **111**, 3, 032001 (2013), [arXiv:1304.3975].

[14] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **115**, 1, 011803 (2015), [arXiv:1503.08203].

[15] K. Chilikin *et al.* (Belle) (2020), [arXiv:2003.08335].

[16] B. Aubert *et al.* (BaBar), Phys. Rev. Lett. **101**, 071801 (2008), [Erratum: Phys.Rev.Lett. 102, 029901 (2009)], [arXiv:0807.1086].

[17] B. Aubert *et al.* (BaBar), Phys. Rev. Lett. **103**, 161801 (2009), [arXiv:0903.1124].

[18] R. Mizuk *et al.* (Belle), Phys. Rev. Lett. **109**, 232002 (2012), [arXiv:1205.6351].

[19] U. Tamponi *et al.* (Belle), Phys. Rev. Lett. **115**, 14, 142001 (2015), [arXiv:1506.08914].

[20] B. G. Fulsom *et al.* (Belle), Phys. Rev. Lett. **121**, 23, 232001 (2018), [arXiv:1807.01201].

[21] I. Adachi *et al.* (Belle), Phys. Rev. Lett. **108**, 032001 (2012), [arXiv:1103.3419].

[22] T. K. Pedlar *et al.* (CLEO), Phys. Rev. Lett. **107**, 041803 (2011), [arXiv:1104.2025].

[23] I. Adachi (Belle), in "8th International Workshop On Heavy Quarkonium (QWG2011) Darmstadt, Germany, October 3-7, 2011," (2011), [arXiv:1110.3934].

[24] G. Aad *et al.* (ATLAS), Phys. Rev. Lett. **108**, 152001 (2012), [arXiv:1112.5154].

[25] V. M. Abazov *et al.* (D0), Phys. Rev. D **86**, 031103 (2012), [arXiv:1203.6034].

[26] R. Aaij *et al.* (LHCb), JHEP **10**, 088 (2014), [arXiv:1409.1408].

[27] A. M. Sirunyan *et al.* (CMS), Phys. Rev. Lett. **121**, 092002 (2018), [arXiv:1805.11192].

[28] G. Aad *et al.* (ATLAS), Phys. Rev. Lett. **113**, 212004 (2014), [arXiv:1407.1032].

[29] A. M. Sirunyan *et al.* (CMS), Phys. Rev. Lett. **122**, 132001 (2019), [arXiv:1902.00571].

[30] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **122**, 232001 (2019), [arXiv:1904.00081].

[31] R. Aaij *et al.* (LHCb), JHEP **07**, 035 (2019), [arXiv:1903.12240].
[32] S. Uehara *et al.* (Belle), Phys. Rev. Lett. **96**, 082003 (2006), [hep-ex/0512035].
[33] B. Aubert *et al.* (BaBar), Phys. Rev. D **81**, 092003 (2010), [arXiv:1002.0281].
[34] K. Abe *et al.* (Belle), Phys. Rev. Lett. **94**, 182002 (2005), [hep-ex/0408126].
[35] J. P. Lees *et al.* (BaBar), Phys. Rev. **D86**, 072002 (2012), [arXiv:1207.2651].
[36] F.-K. Guo and U.-G. Meissner, Phys. Rev. **D86**, 091501 (2012), [arXiv:1208.1134].
[37] S. L. Olsen, Phys. Rev. **D91**, 5, 057501 (2015), [arXiv:1410.6534].
[38] Z.-Y. Zhou, Z. Xiao and H.-Q. Zhou, Phys. Rev. Lett. **115**, 2, 022001 (2015), [arXiv:1501.00879].
[39] R. Aaij *et al.* (LHCb), Phys. Rev. D **102**, 112003 (2020), [arXiv:2009.00026].
[40] K. Chilikin *et al.* (Belle), Phys. Rev. **D95**, 112003 (2017), [arXiv:1704.01872].
[41] B. Aubert *et al.* (BaBar), Phys. Rev. Lett. **95**, 142001 (2005), [hep-ex/0506081].
[42] C. Z. Yuan *et al.* (Belle), Phys. Rev. Lett. **99**, 182004 (2007), [arXiv:0707.2541].
[43] Z. Q. Liu *et al.* (Belle), Phys. Rev. Lett. **110**, 252002 (2013), [arXiv:1304.0121].
[44] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **118**, 9, 092001 (2017), [arXiv:1611.01317].
[45] M. Cleven *et al.*, Phys. Rev. **D90**, 7, 074039 (2014), [arXiv:1310.2190].
[46] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **118**, 9, 092002 (2017), [arXiv:1610.07044].
[47] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **112**, 9, 092001 (2014), [arXiv:1310.4101].
[48] M. Ablikim *et al.* (BESIII), Phys. Rev. **D96**, 3, 032004 (2017), [erratum: Phys. Rev.D99,no.1,019903(2019)], [arXiv:1703.08787].
[49] X. Y. Gao, C. P. Shen and C. Z. Yuan, Phys. Rev. **D95**, 9, 092007 (2017), [arXiv:1703.10351].
[50] X. L. Wang *et al.* (Belle), Phys. Rev. Lett. **99**, 142002 (2007), [arXiv:0707.3699].
[51] X. L. Wang *et al.* (Belle), Phys. Rev. **D91**, 112007 (2015), [arXiv:1410.7641].
[52] J. P. Lees *et al.* (BaBar), Phys. Rev. **D89**, 11, 111103 (2014), [arXiv:1211.6271].
[53] G. Pakhlova *et al.* (Belle), Phys. Rev. Lett. **101**, 172001 (2008), [arXiv:0807.4458].
[54] S. Jia *et al.* (Belle), Phys. Rev. **D100**, 11, 111103 (2019), [arXiv:1911.00671].
[55] K. Chilikin *et al.* (Belle), Phys. Rev. **D88**, 7, 074026 (2013), [arXiv:1306.4894].
[56] K. Chilikin *et al.* (Belle), Phys. Rev. **D90**, 11, 112009 (2014), [arXiv:1408.6457].
[57] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **112**, 22, 222002 (2014), [arXiv:1404.1903].
[58] B. Aubert *et al.* (BaBar), Phys. Rev. **D79**, 112001 (2009), [arXiv:0811.0564].
[59] R. Mizuk *et al.* (Belle), Phys. Rev. **D78**, 072004 (2008), [arXiv:0806.4098].
[60] J. P. Lees *et al.* (BaBar), Phys. Rev. **D85**, 052003 (2012), [arXiv:1111.5919].
[61] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **102**, 242002 (2009), [arXiv:0903.2229].
[62] T. Aaltonen *et al.* (CDF), Mod. Phys. Lett. **A32**, 26, 1750139 (2017), [arXiv:1101.6058].
[63] V. M. Abazov *et al.* (D0), Phys. Rev. **D89**, 1, 012004 (2014), [arXiv:1309.6580].
[64] S. Chatrchyan *et al.* (CMS), Phys. Lett. **B734**, 261 (2014), [arXiv:1309.6920].
[65] J. Brodzicka, Conf. Proc. **C0908171**, 299 (2009), [,299(2009)].
[66] R. Aaij *et al.* (LHCb), Phys. Rev. **D85**, 091103 (2012), [arXiv:1202.5087].
[67] J. P. Lees *et al.* (BaBar), Phys. Rev. **D91**, 1, 012003 (2015), [arXiv:1407.7244].
[68] C. P. Shen *et al.* (Belle), Phys. Rev. Lett. **104**, 112004 (2010), [arXiv:0912.2383].

[69] R. Aaij *et al.* (LHCb), Phys. Rev. **D95**, 1, 012002 (2017), [arXiv:1606.07898].
[70] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **118**, 2, 022003 (2017), [arXiv:1606.07895].
[71] R. Mizuk *et al.* (Belle), JHEP **10**, 220 (2019), [arXiv:1905.05521].
[72] D. Santel *et al.* (Belle), Phys. Rev. **D93**, 1, 011101 (2016), [arXiv:1501.01137].
[73] F.-K. Guo, X.-H. Liu and S. Sakai, Prog. Part. Nucl. Phys. **112**, 103757 (2020), [arXiv:1912.07030].
[74] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **110**, 222001 (2013), [arXiv:1302.6269].
[75] R. Aaij *et al.* (LHCb), Phys. Rev. **D92**, 1, 011102 (2015), [arXiv:1504.06339].
[76] R. Aaij *et al.* (LHCb), Phys. Rev. D **102**, 9, 092005 (2020), [arXiv:2005.13419].
[77] N. Brambilla *et al.*, Eur. Phys. J. **C71**, 1534 (2011), [arXiv:1010.5827].
[78] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **110**, 252001 (2013), [arXiv:1303.5949].
[79] T. Xiao *et al.*, Phys. Lett. **B727**, 366 (2013), [arXiv:1304.3036].
[80] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **112**, 2, 022001 (2014), [arXiv:1310.1163].
[81] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **115**, 11, 112003 (2015), [arXiv:1506.06018].
[82] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **115**, 22, 222002 (2015), [arXiv:1509.05620].
[83] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **111**, 24, 242001 (2013), [arXiv:1309.1896].
[84] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **112**, 13, 132001 (2014), [arXiv:1308.2760].
[85] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **113**, 21, 212002 (2014), [arXiv:1409.6577].
[86] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **115**, 18, 182002 (2015), [arXiv:1507.02404].
[87] A. Bondar *et al.* (Belle), Phys. Rev. Lett. **108**, 122001 (2012), [arXiv:1110.2251].
[88] A. Garmash *et al.* (Belle), Phys. Rev. **D91**, 7, 072003 (2015), [arXiv:1403.0992].
[89] P. Krokovny *et al.* (Belle), Phys. Rev. **D88**, 5, 052016 (2013), [arXiv:1308.2646].
[90] I. Adachi *et al.* (Belle) (2012), [arXiv:1209.6450].
[91] K. F. Chen *et al.* (Belle), Phys. Rev. Lett. **100**, 112001 (2008), [arXiv:0710.2577].
[92] P. Krokovny (Belle Collab.), talk given at Les Rencontres de Physique de la Vallee d'Aoste, La Thuile, Aosta Valley, Italy, 2012.
[93] A. Abdesselam *et al.* (Belle), Phys. Rev. Lett. **117**, 14, 142001 (2016), [arXiv:1508.06562].
[94] M. Cleven *et al.*, Eur. Phys. J. **A47**, 120 (2011), [arXiv:1107.0254].
[95] F. K. Guo *et al.*, Phys. Rev. **D93**, 7, 074031 (2016), [arXiv:1602.00940].
[96] Q. Wang *et al.*, Phys. Rev. D **98**, 7, 074023 (2018), [arXiv:1805.07453].
[97] A. Garmash *et al.* (Belle), Phys. Rev. Lett. **116**, 21, 212001 (2016), [arXiv:1512.07419].