77. Spectroscopy of Mesons Containing Two Heavy Quarks

Revised March 2020 by S. Eidelman (Budker Inst., Novosibirsk; Novosibirsk U.), C. Hanhart (Jülich), J. J. Hernández-Rey (IFIC, Valencia), R.E. Mitchell (Indiana U.), S. Navas (Dp.de Fisica. U. de Granada) and C. Patrignani (Bologna U.).

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. Since that time CLEO-c, BESIII and the B-factories, recently joined by ATLAS, CMS and LHCb, have continued to make groundbreaking observations. For an extensive presentation of the status of heavy quarkonium physics, the reader is referred to several reviews [1–6]. 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 minireview on non-$q\bar{q}$ states. 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 minireview covers the newly discovered states, where "newly" refers to the period since 2002. 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 77.1), near (*cf.* Table 77.2) and above (*cf.* Table 77.3) the lowest open-flavor thresholds.

Table 77.1 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 $h_c(1P)$ 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, $\psi(2S)$.

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 [9] has revisited its analysis of $B \to K\eta_c(2S)$, $\eta_c(2S) \to K\overline{K}\pi$ 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 inflates 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 [10], which did not include interference. Complementing this measurement in B-decay, BaBar [11] updated their previous [12] $\eta_c(2S)$ 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 currently most accurate individual mass measurement is from LHCb using $B^+ \to K^+\bar{p}p$ [13].

Belle reported an observation of the $\psi_2(1D)$ decaying to $\gamma\chi_{c1}$ with J^{PC} presumed to be 2^{--} [14]. This state is listed in Table 77.1 as $\psi_2(3823)$. Its existence was confirmed with high significance by BESIII [15]. 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. This assignment therefore requires experimental confirmation.

The 1^1D_2 state, or the $\eta_{c2}(1D)$, with a mass expected near 3820 MeV, has not been observed yet. Recently Belle performed its search in $B \to \eta_{c2}(1D)K(\pi)$ decays in the mass range 3795-3845 MeV and found no signal [16]. Thus, the $\eta_{c2}(1D)$ remains the only unobserved conventional

Table 77.1: 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 PDG20 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)		
$\eta_c(2S)$		3639.2 ± 1.2	$11.3^{+3.2}_{-2.9}$	$0^+(0^{-+})$	$B \to KX$	$K^0_S K^- \pi^+$	2002	YES
						$\bar{p}p$		
					$e^+e^- \to e^+e^- X$	hadrons		
					$e^+e^- \to J/\psi X$	(see listings)		
$\psi_2(3823)$	$X(3823)$	3822.2 ± 1.2	< 16	$0^-(2^{--})$	$B \to KX$	$\gamma\,\chi_{c1}(1P)$	2013	YES
					$e^+e^- \to \pi^+\pi^- X$			
B_c^+		6274.9 ± 0.8	?	$0(0^-)$	$\bar{p}p \to X...$	$\pi^+ J/\psi$	2007	YES
					$pp \to X...$	(see listings)		
$B_c^+(2S)$		6842 ± 6	?	$0(0^-)$	$pp \to X...$	$B_c^+\pi^+\pi^-$	2014	NO
$\eta_b(1S)$		9399.0 ± 1.3	10^{+5}_{-4}	$0^+(0^{-+})$	$\Upsilon(2S,3S) \to \gamma X$		2008	YES
					$h_b(1P,2P) \to \gamma X$			
$h_b(1P)$		9899.3 ± 0.8	?	$0^-(1^{+-})$	$\Upsilon(10860) \to \pi^+\pi^- X$	$\gamma\eta_b(1S)$	2011	YES
					$\Upsilon(3S) \to \pi^0 X$			
$\eta_b(2S)$		$9999.0^{+4.5}_{-4.0}$	< 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	NO
$\chi_{b1}(3P)$		10512.1 ± 2.3	?	$0^+(1^{++})$	$pp \to X...$	$\gamma\mu^+\mu^-$	2011	YES

charmonium state that does not have open-charm decays.

A new $c\bar{b}$ state was discovered by the ATLAS Collaboration [17]. Its properties are consistent with expectations for the first excited state of the $B_c^\pm$ meson, the $B_c^\pm(2S)$. The real picture appears to be more complicated. The ATLAS state was observed at 6842 ± 6 MeV. Five years later, the CMS collaboration investigated the $B_c^+\pi^+\pi^-$ invariant mass spectrum and observed two close signals consistent with the $B_c^{*+}(2S)$ and $B_c^+(2S)$ states [18]. The two peaks are well resolved (a significance of 6.5 standard deviations), with a measured mass difference of $\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV. The mass of the right peak, $B_c^+(2S)$, is measured to be $6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)$ MeV, where the last term is the uncertainty in the world-average B_c^+ mass. Since the low-energy photon emitted in the $B_c^{*+} \to B_c^+ + \gamma$ radiative decay is not reconstructed, the observed $B_c^{*+}(2S)$ peak has a mass lower than the true value, which remains unknown. Therefore the $B_c^{*+}(2S)$ does not yet appear in the listings. LHCb confirmed the CMS results and measured masses with higher precision [19]. Their signal corresponding to the $B_c^{*+}(2S)$ is observed at $6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)$ MeV with a significance of 6.3 standard deviations. Also here the low energy photon was not observed. The data also show a hint (2.2σ) for a second structure consistent with

Table 77.2: As in Table 77.1, 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 [7] with kind permission, copyright (2011), Springer, and [8] 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
$\chi_{c1}(3872)$	$X(3872)$	3871.69 ± 0.17	< 1.2	$0^+(1^{++})$	$B \to KX$ $p\bar{p} \to X...$ $pp \to X...$ $e^+e^- \to \gamma X$	$\pi^+\pi^- J/\psi$ $3\pi J/\psi$ $D^{*0}\overline{D}^0$ $\gamma J/\psi$ $\gamma\psi(2S)$ $\pi^0\chi_{c1}(1P)$	2003	YES
$Z_c(3900)$		3886.6 ± 2.4	28.2 ± 2.6	$1^+(1^{+-})$	$\psi(4260) \to \pi^- X$ $\psi(4260) \to \pi^0 X$	$\pi^+ J/\psi$ $\pi^0 J/\psi$ $(D\bar{D}^*)^+$ $(D\bar{D}^*)^0$	2013	YES
$X(4020)$	$Z_c(4020)$	4024.1 ± 1.9	13 ± 5	$1^+(?^{?-})$	$\psi(4260, 4360) \to \pi^- X$ $\psi(4260, 4360) \to \pi^0 X$	$\pi^+ h_c$ $\pi^0 h_c$ $(D^*\bar{D}^*)^+$ $(D^*\bar{D}^*)^0$	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

the $B_c^+(2S)$ with a mass $31.0 \pm 1.4(\text{stat}) \pm 0.0(\text{syst})$ higher.

The ground state of bottomonium, $\eta_b(1S)$, was confirmed with a second observation of more than 5σ significance at Belle. In addition, the same experiment collected strong evidence for the $\eta_b(2S)$ [21], but it still needs experimental confirmation at the 5σ level.

Using dipion transitions from the $\Upsilon(10860)$ (Fig. 77.1), Belle simultaneously discovered the $h_b(1P)$, the bottomonium counterpart of the $h_c(1P)$, and the next excited state, the $h_b(2P)$ [20]. The same analysis also showed the $\Upsilon_2(1D)$, the lowest-lying D-wave triplet of the $b\bar{b}$ system. 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, $\psi(4230) \to \pi^+\pi^- J/\psi$. The presence of $\Upsilon(nS)$ peaks in Fig. 77.1 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 $h_b(1P)$ 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. [23]).

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 the mass of the $\Upsilon(10860)$ [24]. After the mass of the $\eta_b(1S)$ was shifted upwards by about 10 MeV based on the new Belle measurements [21] [25], 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 $\Upsilon(4S) \to \eta h_b(1P)$ [25].

Table 77.3: As in Table 77.1, 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
$\psi_3(3842)$		3842.7 ± 0.2	2.79 ± 0.6	$0^+(3^{--})^*$	$pp \to X...$	$D\overline{D}$	2019	NO
$\chi_{c0}(3860)$		3862^{+48}_{-35}	201^{+177}_{-106}	$0^+(0^{++})$	$e^+e^- \to J/\psi X$	$D\overline{D}$	2017	NO
$X(3915)$	$\chi_{c0}(3915)$, $Y(3940)$	3918.4 ± 1.9	20 ± 5	$0^+(0/2^{++})$	$B \to KX$ $e^+e^- \to e^+e^-X$	$\omega J/\psi$	2004	YES
$\chi_{c2}(3930)$	$\chi_{c2}(2P)$, $Z(3930)$	3927.2 ± 2.6	24 ± 6	$0^+(2^{++})$	$e^+e^- \to e^+e^-X$	$D\overline{D}$	2005	YES
$X(3940)$		3942^{+9}_{-8}	37^{+27}_{-17}	$?^?(?^{??})$	$e^+e^- \to J/\psi X$	$D\overline{D}^*$	2007	NO
$X(4050)^\pm$	$Z_1(4050)$	4051^{+24}_{-43}	82^{+51}_{-28}	$1^-(?^{?+})$	$B \to KX$	$\pi^+\chi_{c1}(1P)$	2008	NO
$X(4055)^\pm$	$Z_c(4055)$	4054 ± 3	45 ± 13	$1^+(?^{?-})$	$e^+e^- \to \pi^-X$	$\pi^+\psi(2S)$	2017	NO
$\chi_{c1}(4140)$	$Y(4140)$	4146.8 ± 2.4	22^{+8}_{-7}	$0^+(1^{++})$	$B^+ \to K^+X$ $e^+e^- \to e^+e^-X$	$\phi J/\psi$	2009	YES
$X(4160)$		4156^{+29}_{-25}	139^{+113}_{-65}	$?^?(?^{??})$	$e^+e^- \to J/\psi X$	$D\overline{D}^*$	2007	NO
$Z_c(4200)$		4196^{+35}_{-32}	370^{+99}_{-149}	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$J/\psi\pi^+$	2014	NO
$\psi(4230)$	$Y(4230)$	4218^{+5}_{-4}	59^{+12}_{-10}	$0^-(1^{--})$	$e^+e^- \to X$	$\omega\chi_{c0}(1P)$ $\pi^+\pi^-\psi(2S)$ $\pi^+\pi^-h_c(1P)$	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
$X(4250)^\pm$	$Z_2(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$1^-(?^{?+})$	$B \to KX$	$\pi^+\chi_{c1}(1P)$	2008	NO
$\psi(4260)$	$Y(4260)$	4230 ± 8	55 ± 19	$0^-(1^{--})$	$e^+e^- \to X$	$\pi\pi J/\psi$ $\gamma\chi_{c0}(3872)$	2005	NO
$\chi_{c1}(4274)$	$Y(4274)$	4274^{+8}_{-6}	49 ± 12	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi$	2011	NO
$X(4350)$		$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0^+(?^{?+})$	$e^+e^- \to e^+e^-X$	$\phi J/\psi$	2009	NO
$\psi(4360)$	$Y(4360)$	4368 ± 13	96 ± 7	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2\mathrm{S})$	2007	YES
$\psi(4390)$	$Y(4390)$	$4391.5^{+6.4}_{-6.9}$	$139.5^{+16.2}_{-20.6}$	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-h_c(1P)$	2017	NO
$Z_c(4430)$		4478^{+15}_{-18}	181 ± 31	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$\pi^+\psi(2S)$ π^+J/ψ	2007	YES
$\chi_{c0}(4500)$	$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-29}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi$	2017	NO
$\psi(4660)$	$Y(4660)$, $X(4630)$	4643 ± 9	72 ± 11	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2S)$ $\Lambda_c^+\Lambda_c^-$ $D_s^+D_{s1}(2536)$	2007	YES
$\chi_{c0}(4700)$	$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi$	2017	NO
$\Upsilon(10753)$		10752.7 ± 5.9	$35.5^{+18.0}_{-11.8}$	$0^-(1^{--})$	$e^+e^- \to X$	$\pi\pi\Upsilon(1S,2S,3S)$	2019	NO
$\Upsilon(10860)$	$\Upsilon(5S)$	$10889.9^{+3.2}_{-2.6}$	51^{+6}_{-7}	$0^-(1^{--})$	$e^+e^- \to X$	$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi)$ $\pi\pi\Upsilon(1S,2S,3S)$ $\pi^+\pi^-h_b(1P,2P)$ $\eta\Upsilon(1S,2S)$ $\pi^+\pi^-\Upsilon(1D)$	1985	YES
$\Upsilon(11020)$	$\Upsilon(6S)$	$10992.9^{+10.0}_{-3.1}$	49^{+9}_{-15}	$0^-(1^{--})$	$e^+e^- \to X$	$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi)$ $\pi\pi\Upsilon(1S,2S,3S)$ $\pi^+\pi^-h_b(1P,2P)$	1985	YES

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

The $\chi_{bJ}(nP)$ states have been observed at the LHC by ATLAS [26] and confirmed by D0 [27] 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

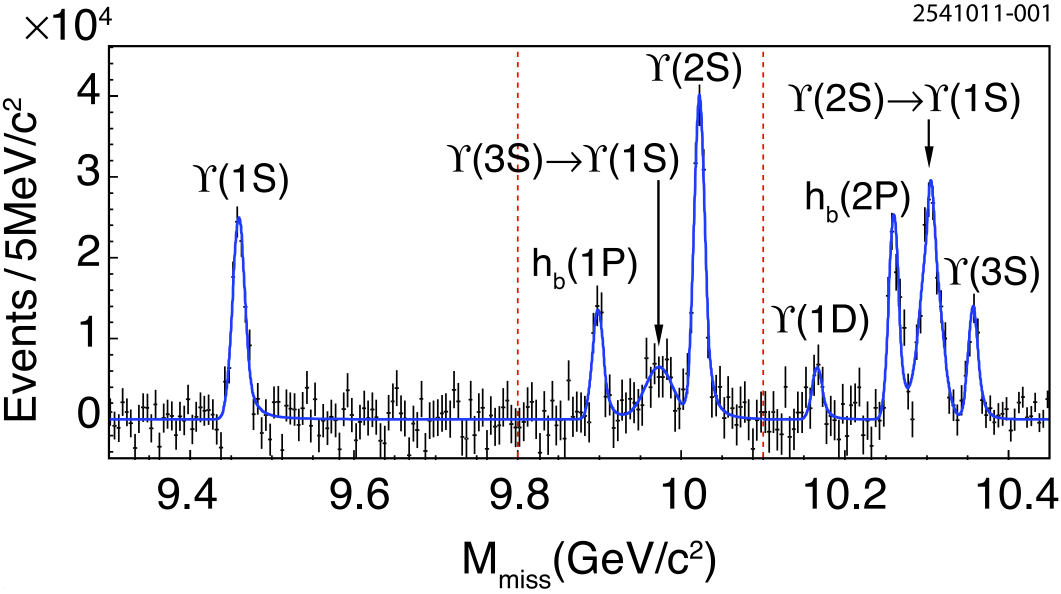

Figure 77.1: From Belle [20], the mass recoiling against $\pi^+\pi^-$ pairs, $M_{\rm miss}$, in e^+e^- collision data taken near the peak of the $\Upsilon(10860)$ (*points with error bars*). The smooth combinatorial and $K^0_S \to \pi^+\pi^-$ background contributions have been subtracted. The fit to the various labeled signal contributions is overlaid (*curve*). Adapted from [20] with kind permission, copyright (2011) The American Physical Society.

mass in the χ_b region. All three J-merged peaks are observed with a 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. 77.2. This marks the first observation of the $\chi_{bJ}(3P)$ triplet, quite near the expected mass. A precise confirmation of this result came from LHCb [28].

A large number of states was discovered recently both near and above the lowest open-flavor thresholds. They are displayed in Table 77.2 and Table 77.3, respectively. With the exception of the tensor state located at 3930 MeV, now called $\chi_{c2}(3930)$, which has properties consistent with those expected for the $\chi_{c2}(2P)$, none of these states can easily be assigned a place in the quark model spectrum of charmonia or bottomonia. At the same time, these states have no universally accepted unconventional interpretation either. The $\chi_{c1}(3872)$, also known as $X(3872)$, is widely studied and seen in many transitions — *c.f.* Table 77.2. Yet its interpretation demands additional experimental attention: after the quantum numbers were fixed at LHCb [29,30], the next experimental challenge will be a measurement of its lineshape.

LHCb observed in prompt proton-proton collisions a new narrow charmonium state, the $X(3842)$ resonance, in the decay modes $X(3842) \to D^0\overline{D}^0$ and $X(3842) \to D^+D^-$ [31]. The mass and width of this state are measured to be $(3842.71\pm0.16\pm0.12)$ MeV and $(2.79\pm0.51\pm0.35)$ MeV, respectively. The observed mass and narrow width is consistent with the interpretation of the new state as the unobserved spin-3 $\psi_3(1^3D_3)$ charmonium state. 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.

Another state (referred to here as the $X(3915)$), was discovered at 3915 MeV [32] and from a subsequent measurement its quantum numbers were determined to be $J^{PC} = 0^{++}$ [33]. This suggests it may be the $\chi_{c0}(2P)$ quark model state, but this interpretation is not generally accepted [34,35]. In addition, it was pointed out in Ref. [36] that if the assumption of helicity-2 dominance

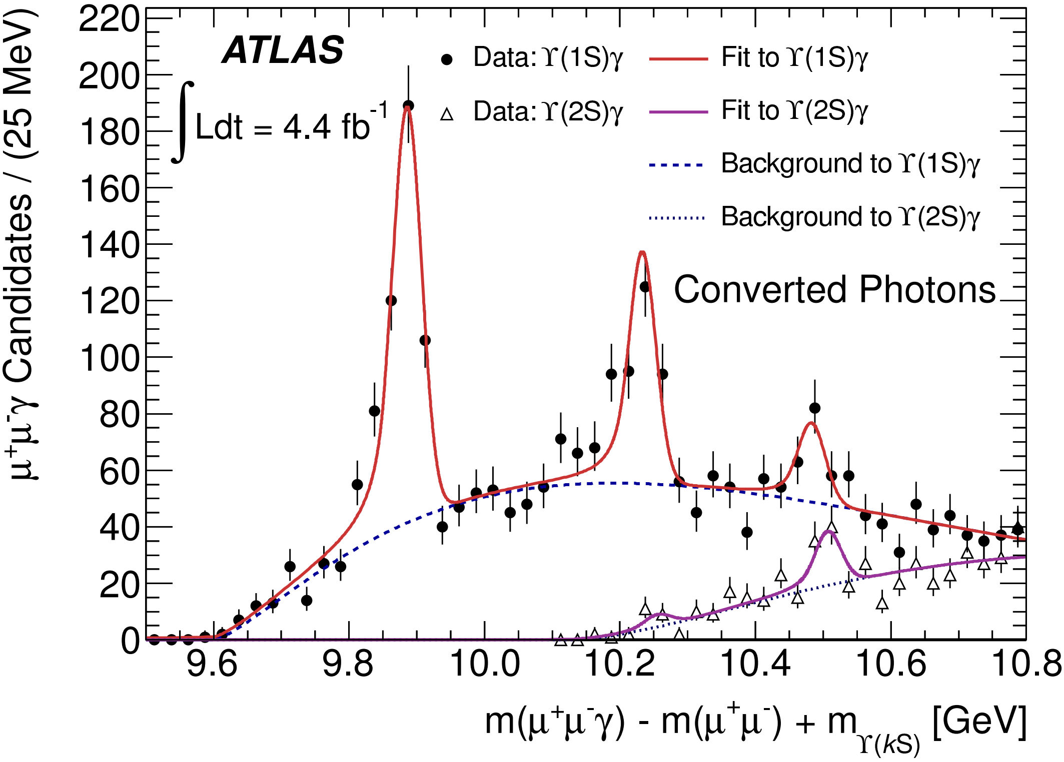

Figure 77.2: From ATLAS [26] pp collision data (*points with error bars*) taken at $\sqrt{s} = 7$ TeV, the effective mass of $\chi_{bJ}(1P, 2P, 3P) \to \gamma\Upsilon(1S, 2S)$ candidates in which $\Upsilon(1S, 2S) \to \mu^+\mu^-$ and the photon is reconstructed as an e^+e^- conversion in the tracking system. Fits (*smooth curves*) show significant signals for each triplet (J-merged) on top of a smooth background. From [26] with kind permission, copyright (2012) The American Physical Society.

is abandoned and instead one allows for a sizable helicity-0 component, a $J^{PC} = 2^{++}$ assignment is possible. This could imply that the state at 3930 MeV (referred to here as the $\chi_{c2}(3930)$) is actually identical to the one at 3915 MeV—but to explain the large helicity-0 component a sizable portion of non-$q\bar{q}$ is necessary [36]. Because of this analysis, the name of the state was changed from $\chi_{c0}(3915)$ back to $X(3915)$. An alternative candidate for the $\chi_{c0}(2P)$ (referred to here as the $\chi_{c0}(3860)$) was reported in Ref. [37] with properties more consistent with expectation: its mass is close to the potential model expectations, it decays to $D\overline{D}$, and the preferred quantum numbers are $J^{PC} = 0^{++}$ (this hypothesis is favored over the 2^{++} one with a 2.5σ significance).

The $\psi(4260)$, also known as $Y(4260)$, and the $\psi(4360)$, also known as $Y(4360)$, are vector states decaying to $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-\psi(2S)$, respectively, yet, unlike most conventional vector charmonia, they do not correspond to enhancements in the e^+e^- hadronic cross section nor decay to $D\overline{D}$. Recently BESIII produced a high-accuracy data set for $e^+e^- \to \pi^+\pi^-J/\psi$ [38], demonstrating that the lineshape in this mass range is highly non-trivial. 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 $\psi(4260)$ [39]. The data of Ref. [38] also called for a significant downward shift of the mass of $\psi(4260)$ no longer justifying a distinction between $\psi(4260)$ and $\psi(4230)$. The latter was discovered earlier in various decay modes, amongst others $h_c(1P)\pi\pi$ [40]. The original mass parameter for the $\psi(4260)$ was the result of a fit to the $\pi^+\pi^-J/\psi$ cross section using a symmetric Breit-Wigner line shape [41]. Therefore, starting from the 2020 Edition of the Review of Particle Physics, we list the measurement of Ref. [38] under the node $\psi(4230)$ and promoted the $\psi(4230)$ to the summary tables to replace the $\psi(4260)$. BESIII also observed the $\chi_{c1}(3872)$, also known as $X(3872)$, in $e^+e^- \to \gamma\chi_{c1}(3872)$ in the $\psi(4230)$ mass range [42], which could allow for additional insight into the structure of both the $\psi(4230)$ as well as the $\chi_{c1}(3872)$ (*c.f.* the minireview on non-$q\bar{q}$ states). BESIII also performed a recent study of the process $e^+e^- \to \pi^+\pi^-\psi(2\mathrm{S})$ and found evidence for a lower mass state, possibly the $\psi(4230)$, in addition to the more dominant $\psi(4360)$ [43].

Note that the data of Ref. [38] 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 see the analysis of the $Y(4008)$ region in Ref. [44], where a wide resonance is also extracted.

Another interesting question is whether a heavier $\pi^+\pi^-\psi(2\mathrm{S})$ state, the $\psi(4660)$, discovered by Belle [45, 46] and confirmed by BaBar [47], is identical to the $\Lambda_c^+\Lambda_c^-$ state observed by Belle with a nearby mass and width [48]. Most probably it is, with $\Lambda_c^+\Lambda_c^-$ just being one more decay mode of the $\psi(4660)$ (*c.f.* the minireview on non-$q\bar{q}$ states for more detail). Note that this is the interpretation adopted in the particle listings.

Belle reported the first observation of a vector charmoniumlike state decaying to $D_s^+D_{s1}(2536)$ with a significance of 5.9σ [49]. Its measured mass and width are $(4625.9^{+6.2}_{-6.0} \pm 0.4)$ MeV and $(49.8^{+13.9}_{-11.5} \pm 4.0)$ MeV, respectively, consistent with those of $\psi(4660)$. Therefore these new data appear now as additional decay mode of $\psi(4660)$ in the listings.

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 $J^P = 1^+$ [50]. From their study of $B^0 \to K^+\pi^- J/\psi$ decays, Belle also found evidence for the decay mode $Z_c(4430) \to \pi J/\psi$ [51], 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 also reported evidence for one more charged state, dubbed $Z_c(4200)$, decaying to $\pi J/\psi$. The existence of the $Z_c(4430)$ in $\pi\psi(2S)$ as well as its quantum number assignments were confirmed at LHCb [52] with much higher statistics. Improved values for the mass and width of the $Z_c(4430)$ from LHCb are 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 [53].

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 [54]. These were originally called the $Z_1(4050)^\pm$ and the $Z_2(4250)^\pm$, but are referred to in Table 77.3 as $X(4050)^\pm$ and $X(4250)^\pm$. These states were also not confirmed by BaBar [55]. 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 on product branching fractions that are not inconsistent with Belle's measured rates. The situation remains unresolved.

In addition to the Z_c states discussed above, in 2013 a state named $Z_c(3900)$ was unearthed in the charmonium region at BESIII [56] and Belle [41]. The corresponding spectrum from BESIII is shown in Fig. 77.3. Ref. [57] confirmed this finding and also provided evidence for a neutral partner. A nearby signal was also seen in the $D\overline{D}^*$ channel [58] whose quantum numbers were fixed to 1^{+-}. BESIII reported its neutral partner in both $J/\psi\pi^0$ [59] and $D\overline{D}^*$ [60] 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 Table 77.2, 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 — $h_c\pi^\pm$ [61] and $(D^*\overline{D}^*)^\pm$ [62]. The neutral partners have also been observed by BESIII

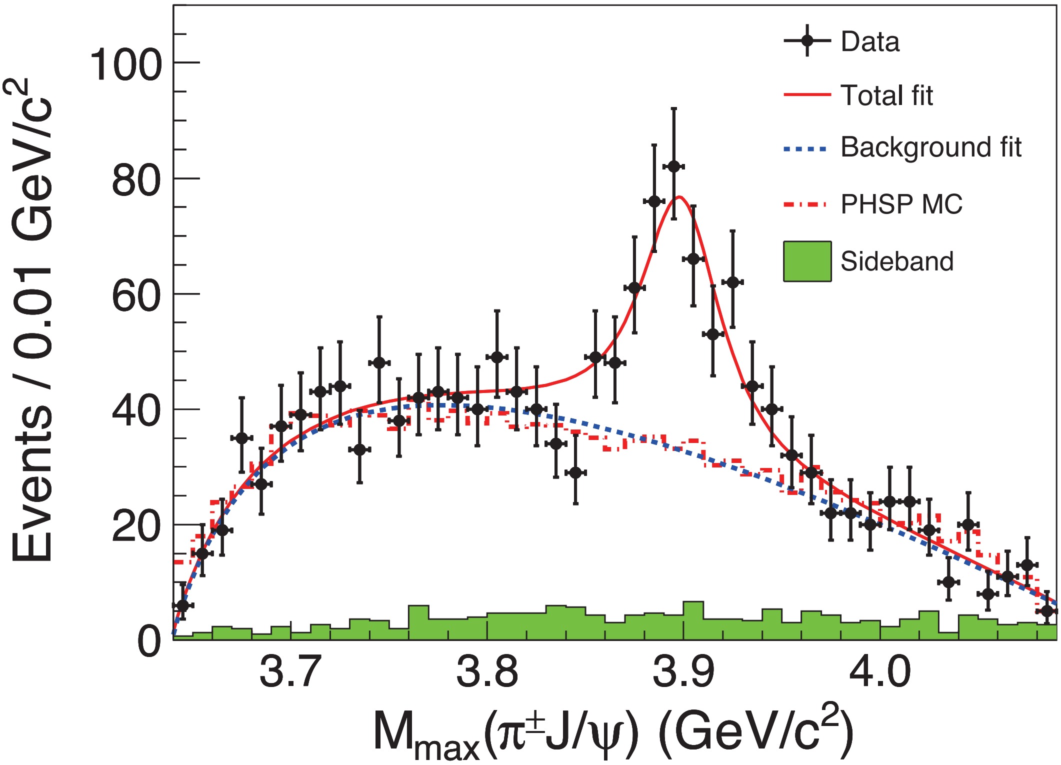

Figure 77.3: $J/\psi\pi$ invariant mass distributions from BES-III [56] e^+e^- collision data taken near the peak of the $Y(4260)$. Adapted from [56] with kind permission, copyright (2013) The American Physical Society.

in the $h_c\pi^0$ [63] and $(D^*\overline{D}^*)^0$ [64] 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 clearly challenge a possible $D\bar{D}^*$–molecular interpretation. Finally, 3.5σ evidence for one more charged charmoniumlike state at 4055 MeV decaying into $\psi(2S)\pi^\pm$ was reported by Belle in their analysis of the process $e^+e^- \to \psi(2S)\pi^+\pi^-$ [46]. This state was confirmed by BESIII, although there appears to be complications in the Dalitz plot requiring further investigation [43].

The $Y(4140)$ observed in 2008 by CDF [65] [66] was confirmed at D0 and CMS [67] [68]. However, a second structure, the $Y(4274)$, could not be established unambiguously. Neither of the two states was seen in B decays at Belle [69], LHCb [70] and BaBar [71] or in $\gamma\gamma$ collisions at Belle [72]. The real breakthrough happened recently when LHCb performed a full amplitude analysis of $B^+ \to J/\psi\phi K^+$ with $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ decays and showed that the data cannot be described in a model that contains only excited kaon states decaying into ϕK^+ [73] [74]. 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 $\chi_{c0}(4700)$).

New results on the η_b, h_b, and Z_b mostly come from Belle [20, 21], [23–25], [75–81], 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 $h_b(1P) \to \gamma\eta_b$.

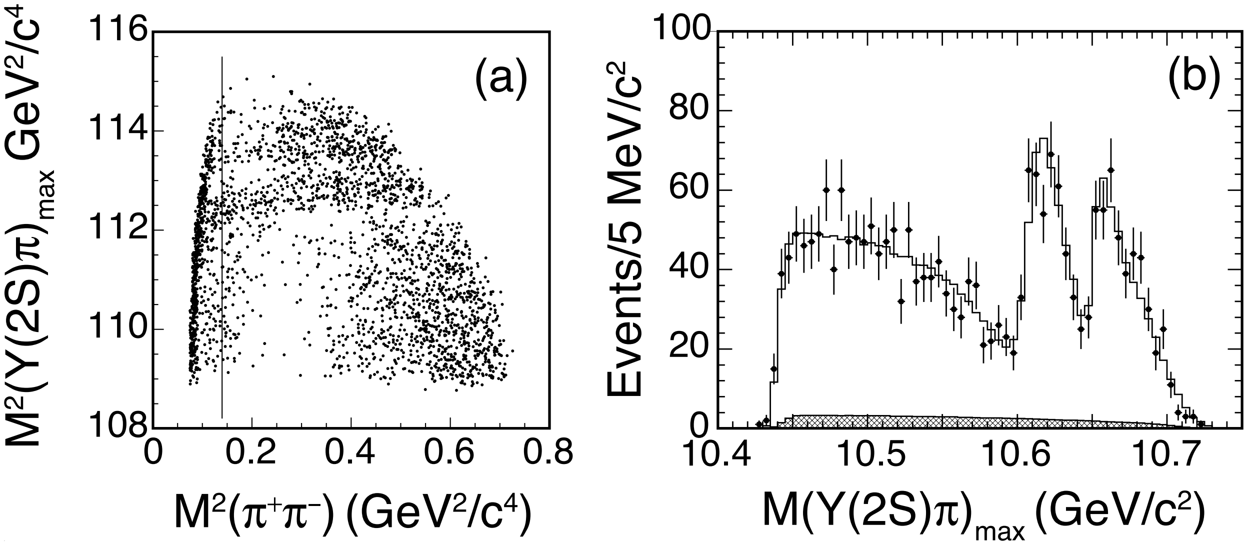

Figure 77.4: From Belle [75] e^+e^- collision data taken near the peak of the $\Upsilon(10860)$ for events with a $\pi^+\pi^-$-missing mass consistent with an $\Upsilon(2S) \to \mu^+\mu^-$, (a) the maximum of the two possible single $\pi^\pm$-missing-mass-squared combinations vs. the $\pi^+\pi^-$-mass-squared; 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 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. Adapted from [75] with kind permission, copyright (2011) The American Physical Society.

Belle soon noticed that, for events in the peaks of Fig. 77.1, there seemed to be two intermediate charged states. For example, Fig. 77.4 shows a Dalitz plot for events restricted to the $\Upsilon(2S)$ region of $\pi^+\pi^-$ recoil mass, with $\Upsilon(2S) \to \mu^+\mu^-$ [75]. 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. 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 [76], 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, respectively, more refined analyses find pole locations right below the corresponding thresholds either on the physical [82] or the unphysical sheet [83]. Regardless of their proximity to the corresponding thresholds, both states predominantly decay into these open-flavor channels [78] [84] with branching fractions that exceed 80% and 70%, respectively, at 90% CL. This feature provides strong evidence for their molecular nature.

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 [85]. They observed with a 5.2σ significance a new structure in the energy dependence of the cross sections. If described by a Breit-Wigner function, its mass and width are found to be $(10752.7 \pm 5.9^{+0.7}_{-1.1})$ MeV/ and $(35.5^{+17.6+3.9}_{-11.3-3.3})$ MeV. The new structure could have a resonant origin and correspond to a signal for 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 some complicated rescattering.

References

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

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

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

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

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

[6] N. Brambilla *et al.* (2019), [arXiv:1907.07583].

[7] N. Brambilla *et al.*, Eur. Phys. J. **C71**, 1534 (2011), [arXiv:1010.5827].

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

[9] A. Vinokurova *et al.* (Belle), Phys. Lett. **B706**, 139 (2011), [arXiv:1105.0978].

[10] S. K. Choi *et al.* (Belle), Phys. Rev. Lett. **89**, 102001 (2002), [Erratum: Phys. Rev. Lett.89,129901(2002)], [hep-ex/0206002].

[11] P. del Amo Sanchez *et al.* (BaBar), Phys. Rev. **D84**, 012004 (2011), [arXiv:1103.3971].

[12] B. Aubert *et al.* (BaBar), Phys. Rev. Lett. **92**, 142002 (2004), [hep-ex/0311038].

[13] R. Aaij *et al.* (LHCb), Phys. Lett. **B769**, 305 (2017), [arXiv:1607.06446].

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

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

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

[17] G. Aad *et al.* (ATLAS), Phys. Rev. Lett. **113**, 21, 212004 (2014), [arXiv:1407.1032].

[18] A. M. Sirunyan *et al.* (CMS), Phys. Rev. Lett. **122**, 13, 132001 (2019), [arXiv:1902.00571].

[19] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **122**, 23, 232001 (2019), [arXiv:1904.00081].

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

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

[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] D. Santel *et al.* (Belle), Phys. Rev. **D93**, 1, 011101 (2016), [arXiv:1501.01137].

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

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

[27] V. M. Abazov *et al.* (D0), Phys. Rev. **D86**, 031103 (2012), [arXiv:1203.6034].

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

[29] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **110**, 222001 (2013), [arXiv:1302.6269].

[30] R. Aaij *et al.* (LHCb), Phys. Rev. **D92**, 1, 011102 (2015), [arXiv:1504.06339].

[31] R. Aaij *et al.* (LHCb), JHEP **07**, 035 (2019), [arXiv:1903.12240].

[32] K. Abe *et al.* (Belle), Phys. Rev. Lett. **94**, 182002 (2005), [hep-ex/0408126].

[33] J. P. Lees *et al.* (BaBar), Phys. Rev. **D86**, 072002 (2012), [arXiv:1207.2651].

[34] F.-K. Guo and U.-G. Meissner, Phys. Rev. **D86**, 091501 (2012), [arXiv:1208.1134].

[35] S. L. Olsen, Phys. Rev. **D91**, 5, 057501 (2015), [arXiv:1410.6534].

[36] Z.-Y. Zhou, Z. Xiao and H.-Q. Zhou, Phys. Rev. Lett. **115**, 2, 022001 (2015), [arXiv:1501.00879].

[37] K. Chilikin *et al.* (Belle), Phys. Rev. **D95**, 112003 (2017), [arXiv:1704.01872].

[38] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **118**, 9, 092001 (2017), [arXiv:1611.01317].

[39] M. Cleven *et al.*, Phys. Rev. **D90**, 7, 074039 (2014), [arXiv:1310.2190].

[40] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **118**, 9, 092002 (2017), [arXiv:1610.07044].

[41] Z. Q. Liu *et al.* (Belle), Phys. Rev. Lett. **110**, 252002 (2013), [arXiv:1304.0121].

[42] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **112**, 9, 092001 (2014), [arXiv:1310.4101].

[43] M. Ablikim *et al.* (BESIII), Phys. Rev. **D96**, 3, 032004 (2017), [erratum: Phys. Rev.D99,no.1,019903(2019)], [arXiv:1703.08787].

[44] X. Y. Gao, C. P. Shen and C. Z. Yuan, Phys. Rev. **D95**, 9, 092007 (2017), [arXiv:1703.10351].

[45] X. L. Wang *et al.* (Belle), Phys. Rev. Lett. **99**, 142002 (2007), [arXiv:0707.3699].

[46] X. L. Wang *et al.* (Belle), Phys. Rev. **D91**, 112007 (2015), [arXiv:1410.7641].

[47] J. P. Lees *et al.* (BaBar), Phys. Rev. **D89**, 11, 111103 (2014), [arXiv:1211.6271].

[48] G. Pakhlova *et al.* (Belle), Phys. Rev. Lett. **101**, 172001 (2008), [arXiv:0807.4458].

[49] S. Jia *et al.* (Belle), Phys. Rev. **D100**, 11, 111103 (2019), [arXiv:1911.00671].

[50] K. Chilikin *et al.* (Belle), Phys. Rev. **D88**, 7, 074026 (2013), [arXiv:1306.4894].

[51] K. Chilikin *et al.* (Belle), Phys. Rev. **D90**, 11, 112009 (2014), [arXiv:1408.6457].

[52] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **112**, 22, 222002 (2014), [arXiv:1404.1903].

[53] B. Aubert *et al.* (BaBar), Phys. Rev. **D79**, 112001 (2009), [arXiv:0811.0564].

[54] R. Mizuk *et al.* (Belle), Phys. Rev. **D78**, 072004 (2008), [arXiv:0806.4098].

[55] J. P. Lees *et al.* (BaBar), Phys. Rev. **D85**, 052003 (2012), [arXiv:1111.5919].

[56] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **110**, 252001 (2013), [arXiv:1303.5949].

[57] T. Xiao *et al.*, Phys. Lett. **B727**, 366 (2013), [arXiv:1304.3036].

[58] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **112**, 2, 022001 (2014), [arXiv:1310.1163].

[59] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **115**, 11, 112003 (2015), [arXiv:1506.06018].

[60] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **115**, 22, 222002 (2015), [arXiv:1509.05620].

[61] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **111**, 24, 242001 (2013), [arXiv:1309.1896].

[62] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **112**, 13, 132001 (2014), [arXiv:1308.2760].

[63] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **113**, 21, 212002 (2014), [arXiv:1409.6577].

[64] M. Ablikim *et al.* (BESIII), Phys. Rev. Lett. **115**, 18, 182002 (2015), [arXiv:1507.02404].

[65] T. Aaltonen *et al.* (CDF), Phys. Rev. Lett. **102**, 242002 (2009), [arXiv:0903.2229].

[66] T. Aaltonen *et al.* (CDF), Mod. Phys. Lett. **A32**, 26, 1750139 (2017), [arXiv:1101.6058].

[67] V. M. Abazov *et al.* (D0), Phys. Rev. **D89**, 1, 012004 (2014), [arXiv:1309.6580].

[68] S. Chatrchyan *et al.* (CMS), Phys. Lett. **B734**, 261 (2014), [arXiv:1309.6920].

[69] J. Brodzicka, Conf. Proc. **C0908171**, 299 (2009), [,299(2009)].

[70] R. Aaij *et al.* (LHCb), Phys. Rev. **D85**, 091103 (2012), [arXiv:1202.5087].

[71] J. P. Lees *et al.* (BaBar), Phys. Rev. **D91**, 1, 012003 (2015), [arXiv:1407.7244].

[72] C. P. Shen *et al.* (Belle), Phys. Rev. Lett. **104**, 112004 (2010), [arXiv:0912.2383].

[73] R. Aaij *et al.* (LHCb), Phys. Rev. **D95**, 1, 012002 (2017), [arXiv:1606.07898].

[74] R. Aaij *et al.* (LHCb), Phys. Rev. Lett. **118**, 2, 022003 (2017), [arXiv:1606.07895].

[75] A. Bondar *et al.* (Belle), Phys. Rev. Lett. **108**, 122001 (2012), [arXiv:1110.2251].

[76] A. Garmash *et al.* (Belle), Phys. Rev. **D91**, 7, 072003 (2015), [arXiv:1403.0992].

[77] P. Krokovny *et al.* (Belle), Phys. Rev. **D88**, 5, 052016 (2013), [arXiv:1308.2646].

[78] I. Adachi *et al.* (Belle) (2012), [arXiv:1209.6450].

[79] K. F. Chen *et al.* (Belle), Phys. Rev. Lett. **100**, 112001 (2008), [arXiv:0710.2577].

[80] P. Krokovny (Belle Collab.), talk given at Les Rencontres de Physique de la Vallee d'Aoste, La Thuile, Aosta Valley, Italy, 2012.

[81] A. Abdesselam *et al.* (Belle), Phys. Rev. Lett. **117**, 14, 142001 (2016), [arXiv:1508.06562].

[82] M. Cleven *et al.*, Eur. Phys. J. **A47**, 120 (2011), [arXiv:1107.0254].

[83] F. K. Guo *et al.*, Phys. Rev. **D93**, 7, 074031 (2016), [arXiv:1602.00940].

[84] A. Garmash *et al.* (Belle), Phys. Rev. Lett. **116**, 21, 212001 (2016), [arXiv:1512.07419].

[85] R. Mizuk *et al.* (Belle), JHEP **10**, 220 (2019), [arXiv:1905.05521].