# RECENT PROGRESS IN CHARMONIUM STUDIES*

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We review recent developments in studies of charmonium and charmonium-like states at $e^+e^-$ and hadronic colliders.

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## 1. Introduction

$B$ factories were designed to study CP violation in the $B\bar{B}$ system operating at the peak of the $\Upsilon(4S)$ resonance. However, already since the time when the ARGUS and CLEO experiments started running in this energy region, it has been known that much richer physics was accessible in this and other energy domains: $\gamma\gamma$ collisions leading to formation of mesons made of light and heavy quarks, $\tau$ lepton decays, charm, narrow $\Upsilon$ decays, *etc.*

Huge statistics collected by BaBar ($\sim$500 fb$^{-1}$) and Belle ($\sim$ 1000 fb$^{-1}$) made possible principally new studies, with a lot of interesting results in, *e.g.*, $\gamma\gamma \to c\bar{c}$, initial-state radiation (ISR) to $q\bar{q}$ and $c\bar{c}$ leading to spectacular observations in the $c\bar{c}$ and $b\bar{b}$ systems with many new states found.

Progress of experiment stimulated in its turn theory resulting in development of various models to explain new effects: tetraquark, hybrid, molecules, hadrocharmonium or, alternatively, effects of close thresholds, coupled channels and rescattering.

Recently, contributions to the field started coming also from hadronic colliders (Tevatron and LHC) as well as from the BESIII experiment at the Beijing tau-charm factory.

In this brief review, we focus on the recent experimental developments in charmonium spectroscopy. More details on the subject can be found in Refs. [1–3].

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## 2. Charmonium

Ten $c\bar{c}$ states were well established by 1980 after the discovery of the first two narrow charmonia in 1974: $\eta_c(1S)$, $J/\psi$, $\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$ below and $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ above the open charm threshold.

After that, for more than 20 years, various experimental information was collected on these states and with $\eta_c(2S)$ (discovered in 2002) and $h_c(1P)$ (reliably established in 2005), the $c\bar{c}$ system seemed completely understood (see Fig. 1), but many new states decaying to charmonia plus other light mesons rather than to open charm were unexpectedly found. For some of them, there is no place in the charmonium spectrum expected in potential models and they were dubbed charmonium-like states.

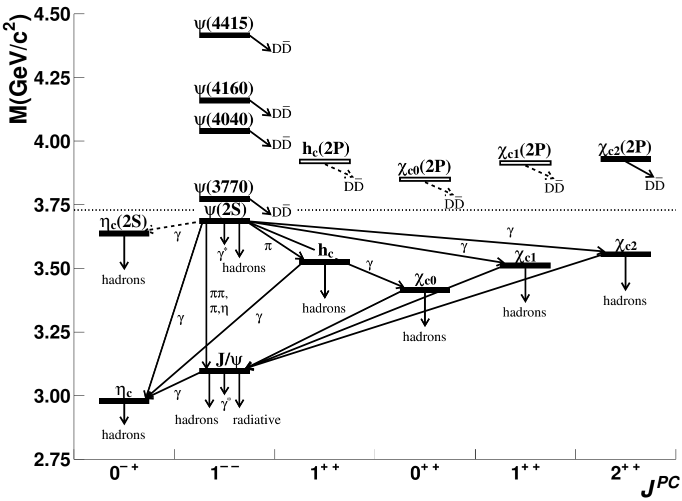


Fig. 1. Charmonium system.

Among the broad states above the open charm threshold only the $\psi(3770)$ is relatively well studied, while the properties of the three other spin-1 states need a much more detailed study [4, 5].

### *2.1. New Y states*

The family of spin-1 charmonia started increasing after intensive use of ISR in high-luminosity experiments at the $B$ factories. First, BaBar reported an observation of the $Y(4260)$ state decaying to $J/\psi\pi^+\pi^-$ [6] soon confirmed by CLEO [7] and Belle [8], the latter also observing an additional structure at 4008 MeV. Later, BaBar discovered the $Y(4360)$ resonance decaying to $\psi(2S)\pi^+\pi^-$ [9], also confirmed by Belle [10], which reported an additional $\psi(2S)\pi^+\pi^-$ state at higher mass — $Y(4660)$. Soon after that, Belle discovered a near-threshold enhancement in the $\Lambda_c^+\Lambda_c^-$ system with parameters close to those of the $Y(4660)$, not excluding a possibility that another decay mode of the $Y(4660)$ has been observed [11].

Figure 2 shows the spectrum of $J/\psi(l^+l^-)\pi^+\pi^-$ invariant masses (left) and the corresponding cross section after background subtraction (right) in a recent analysis of the process $e^+e^- \to J/\psi\pi^+\pi^-(\gamma)$ using almost full data sample collected at Belle [12]. The additional structure near 4000 MeV is confirmed. It remains unclear why the $Y(4260)$ decays into $J/\psi\pi\pi$ only (there is also weak evidence for the $J/\psi K\bar{K}$ decay modes [5]) since the extensive search for many other possible decay modes did not reveal any significant signals.

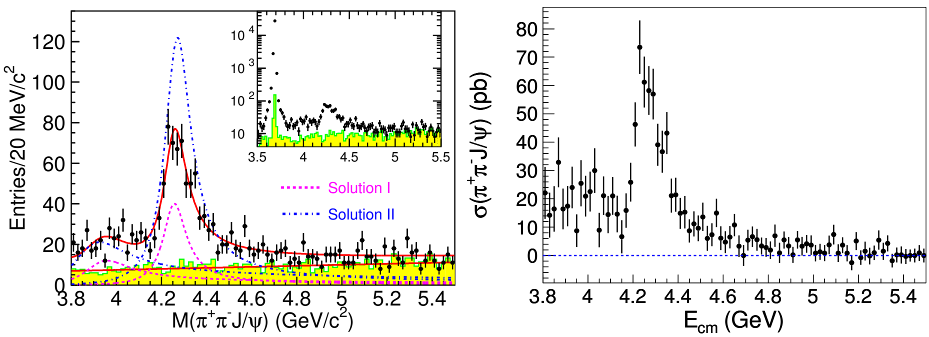


Fig. 2. Study of $e^+e^- \to J/\psi\pi^+\pi^-(\gamma)$ at Belle [12]: (left) the $J/\psi(l^+l^-)\pi^+\pi^-$ invariant masses, (right) the total cross section after background subtraction.

In Fig. 3 (left), we show the cross section of $e^+e^- \to \psi(2S)\pi^+\pi^-(\gamma)$ based on the recent analysis performed at Belle with almost full statistics [13]. The right plot shows the cross section of the $\Lambda_c^+\Lambda_c^-$ production [11]. After recent confirmation of the $Y(4660)$ existence [14], only the $\Lambda_c^+\Lambda_c^-$ structure of Belle remains unconfirmed.

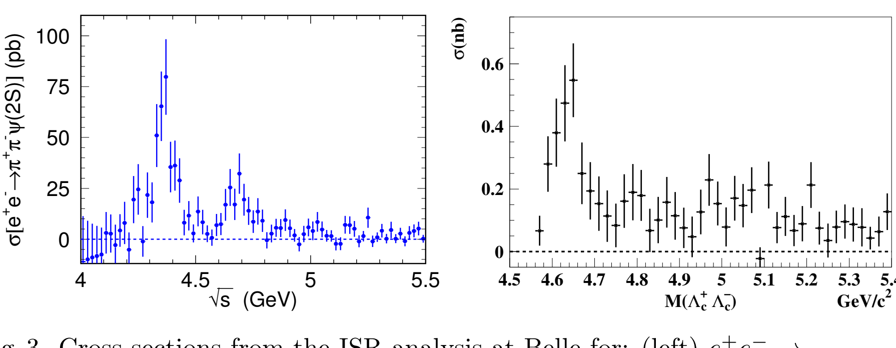


Fig. 3. Cross sections from the ISR analysis at Belle for: (left) $e^+e^- \to \psi(2S)\pi^+\pi^-(\gamma)$ [13], (right) $e^+e^- \to \Lambda_c^+\Lambda_c^-(\gamma)$ [11].

### 2.2. Enigmatic $X(3872)$

In 2003, Belle reported an observation of the narrow $J/\psi\pi^+\pi^-$ state in $B$ decays [15], see Fig. 4. It was soon confirmed by BaBar [16], CDF [17], D0 [18], LHCb [19] and CMS [20]. Until now, its origin is not clear despite numerous experimental and theoretical efforts.

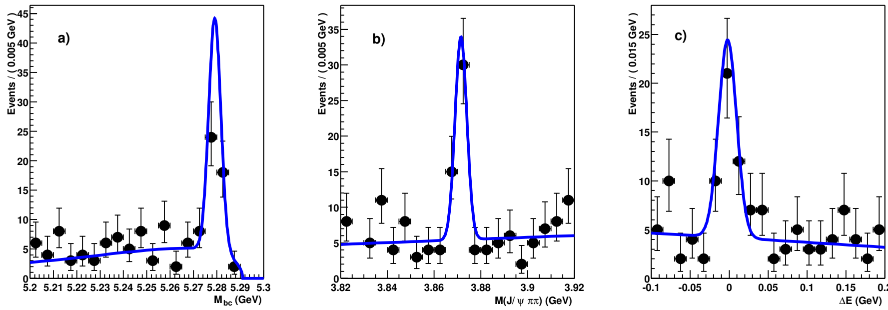


Fig. 4. Discovery of $X(3872)$ at Belle [15].

Some well-established, but not well-understood properties of the $X(3872)$:

— its decays violate isospin since both decays with 2 and 3 pions are found;

— it decays to $J/\psi\gamma$, therefore $C = +1$;

— a multidimensional spin-parity analysis at the LHCb gave $J^{PC} = 1^{++}$ [21, 22];

— it decays to $\psi(2S)\gamma$ with the ratio $\mathcal{B}(\psi(2S)\gamma)/\mathcal{B}(J/\psi\gamma) = 2.46\pm0.64\pm0.29$ [23];

— its mass is very close to the $D^0\bar{D}^{*0}$ threshold and this decay mode has the largest branching [24, 25];

— it does not decay to $\chi_{c1}\gamma$, $D\bar{D}$, $\gamma\gamma$, $e^+e^-$;

— it has no charged partners, so is not an isovector.

All these properties are very difficult to accommodate in any of the existing theoretical models trying to explain the $X(3872)$ origin. Possible interpretations (in arbitrary order): an S-wave $D^0\bar{D}^{*0}$ molecule (loosely bound $[c\bar{q}][\bar{c}q]$), a tetraquark (tightly bound $[cq][\bar{c}\bar{q}]$), a hybrid ($q\bar{q}$-gluon state), threshold effect (cusp), hadrocharmonium — $c\bar{c}$ $(J/\psi,\ldots)$ in the excited light-hadron matter. The $\chi_{c1}(2P)(1^{++})$ interpretation is not very likely considering the decay pattern, mass and observation of $Z(3930) = \chi_{c2}(2P)$. One of the very popular recent explanations is that the $X(3872)$ is a $D^0\bar{D}^{*0}$ molecule mixed with $c\bar{c}$.

### 2.3. Other charmonium-like states

An interesting state was found by CDF in $B$-meson decays to $J/\psi\phi K^+$ [26, 27], see Fig. 5. This state is in a way unique since it consists of two bound states of relatively heavy quarks. It was not confirmed by Belle in $\gamma\gamma$ [28] and LHCb in $B$ decays [29], but was reported by D0 [30] and CMS [31].

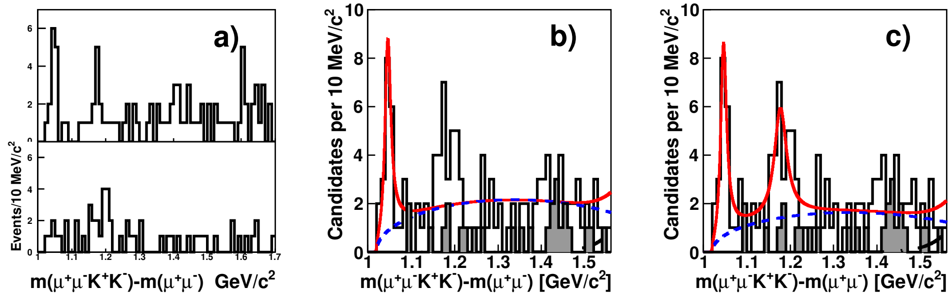


Fig. 5. $Y(4140)$ at CDF [27].

Belle was looking for $\chi_{c1}\gamma$, $\chi_{c2}\gamma$ decays of the $X(3872)$ in $B$ decays and found a new state at 3820 MeV in the $\chi_{c1}\gamma$ final state in addition to the $\psi(2S)$, see Fig. 6. There is no signal at 3872 MeV in both modes, however. They claim $3.8\sigma$ evidence for a new narrow state at $3823.1 \pm 1.8 \pm 0.7$ MeV [32]. All its properties are consistent with it being a $1^3D_2$ or $\psi(1D)$ ($\psi_2$) state with $J^{PC} = 2^{--}$ expected at 3810–3840 MeV. It is narrow because $M < m_D + m_{\bar{D}^*}$ and decay into $D\bar{D}$ is forbidden by $P$-parity. They also determine that $\Gamma(X(3872) \to \chi_{c1}\gamma)/\Gamma(X(3872) \to J/\psi\pi^+\pi^-) < 0.26$ at 90% C.L. setting a constraint on the $C$-odd partner of $X(3872)$.

This $1^3D_2$ state was also confirmed by BESIII [33].

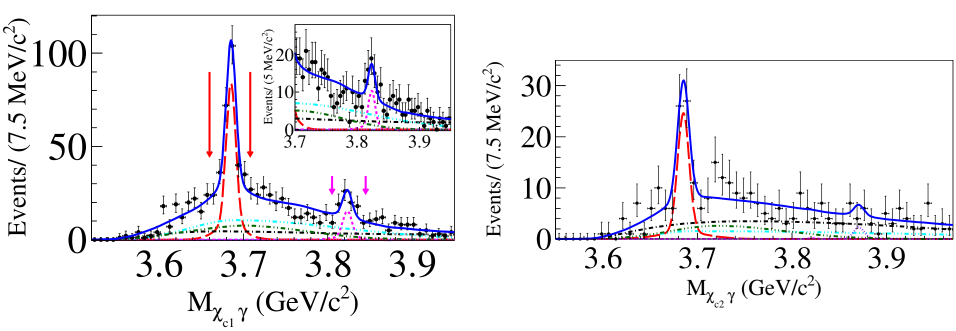


Fig. 6. $X(3823)$ at Belle [32].

### *2.4. Charged charmonium-like states*

The very first charged charmonium-like state $Z(4430)^{\pm}$ decaying to $\psi(2S)\pi^{\pm}$ was observed by Belle in $B \to K\ \psi(2S)\pi^{\pm}$ decays using an integrated luminosity of 605 fb$^{-1}$, see the left plot in Fig. 7 [34].

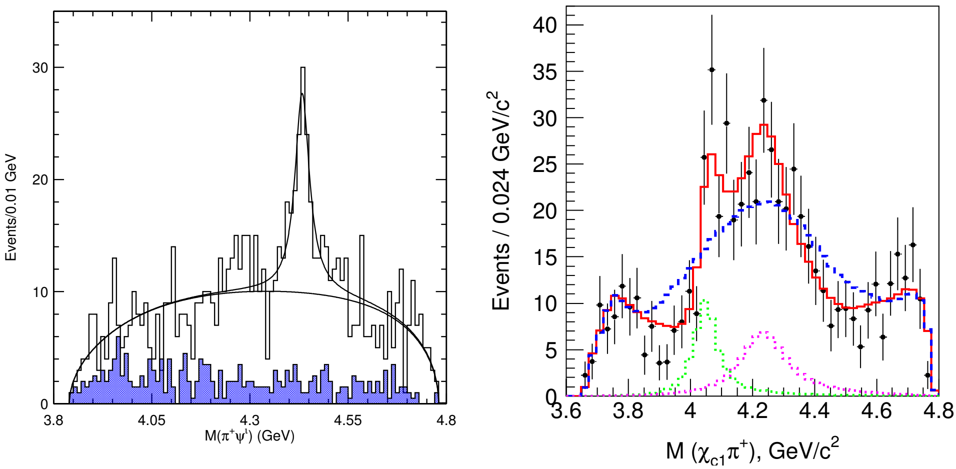


Fig. 7. Exotic charged states at Belle: (left) observation of $Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}$ [34], (right) $\chi_{c1}\pi^{\pm}$ states [40].

It was confirmed by Dalitz plot analysis of the same data sample in Ref. [35], but not seen by BaBar with 413 fb$^{-1}$ [36].

It was finally confirmed at the LHCb [37], which has also determined its $J^P$ to be $1^+$ repeating with much higher confidence level the conclusion of Belle [38]. Finally, in Ref. [39], Belle has also reported evidence for the $J/\psi\pi^{\pm}$ decay of this state as well as an observation of the $Z(4200)^{\pm} \to J/\psi\pi^{\pm}$.

With 605 fb$^{-1}$, Belle also observed two charged states decaying to $\chi_{c1}\pi^{\pm}$ in $\bar{B}^0 \to K^- X^+(\chi_{c1}\pi^+)$ with $X(4050)^+$ and $X(4250)^+$, see the right plot in Fig. 7 [40]. However, BaBar did not observe them with 429 fb$^{-1}$ [41], but did not refute them either since their sensitivity to the process was lower than that of Belle.

Finally, two more exotic charmonium-like states were discovered at BESIII. First, they reported a $Z_c(3900)^{\pm}$ state decaying to $J/\psi\pi^{\pm}$ [42] immediately confirmed by Belle [12], see Fig. 8. Later, they observed another charged state in the $h_c\pi^{\pm}$ mode at 4020 MeV [43]. For both, they also observed other decay modes $(D\bar{D}^*)^{\pm}$ for the $Z_c(3900)^{\pm}$ [44] and $(D^*\bar{D}^*)^{\pm}$ for the $Z_c(4020)^{\pm}$ [45] as well as neutral partners determining their isovector nature [46]. Both charged and neutral $Z_c(3900)$ states were reported by the group that used CLEO-c data [47].

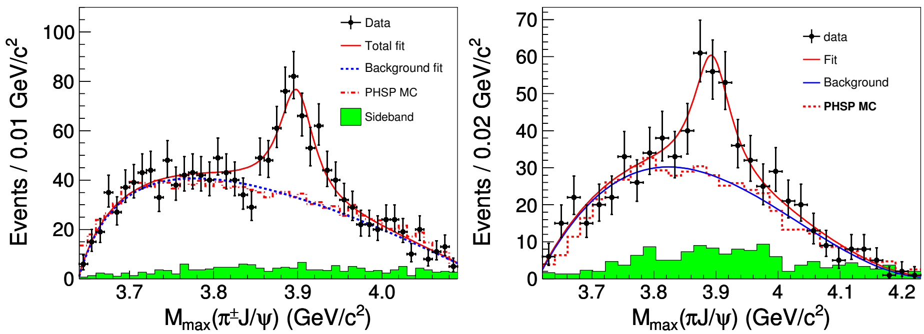


Fig. 8. $J/\psi\pi$ states at 3900 MeV observed at BESIII [42] and Belle [12].

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