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Charmonium Spectroscopy, an experimental review

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The flow of observations concerning charmonium states that do not match regular spectroscopy is still copious, leading to new horizons in the understanding of multi-quark states. This paper summarizes the state of the art in this field.

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In the past few years the field of hadron spectroscopy has seen renewed interest due to the pubblication, initially mostly from B-Factories, of evidences of states that do not match regular spectroscopy, but are rather candidates for bound states with additional quarks or gluons. Currently, the most likely possible states beyond the mesons and the baryons are (you can find a review in [1]):

- hybrids: bound states of a quark-antiquark pair and a number of gluons. The lowest lying state is expected to have quantum numbers $J^{PC} = 0^{+-}$. The impossibility of a quarkonium state to assume these quantum numbers (see below) makes this a unique signature for hybrids. Alternatively a good signature would be the preference to decay into a quarkonium and a state that can be produced by the excited gluons (e.g. $\pi^+\pi^-$ pairs).

- molecules: bound states of two mesons, usually represented as $[Q\bar{q}][q'\bar{Q}]$, where Q is the heavy quark. The system would be stable if the binding energy would set the mass of the states below the sum of the two meson masses. None of the observed states have this characteristic, while some of them have masses slightly above the sum of the constituents. In this case the two mesons can be bound by pion exchange. This means that only states decaying strongly into pions can bind with other mesons (e.g. there could be D^*D states), and that the bound state could decay into it's constituents.

- tetraquarks: a quark pair bound with an antiquark pair, usually represented as $[Qq][\bar{q}'\bar{Q}]$. A full nonet of states is predicted for each spin-parity, i.e. many states are expected. There is no need for these states to be close to any threshold.

In setting after these states one must also beware of threshold effects, where amplitudes might be enhanced when new hadronic final states become possible.

This paper reviews the experimental state of the art in charmonium spectroscopy with emphasis on the measurements that are most likely to cast more light on the understanding of the global picture.

1. Regular Charmonium Spectroscopy

The heavy quark inside these bound states has low enough energy that the corresponding spectroscopy is close to the non-relativistic interpretations of the atoms. The quantum numbers that are more appropriate to characterize a state are therefore, in decreasing order of energy splitting among different eigenstates, the radial excitation (n), the spatial angular momentum L, the spin S and the total angular momentum J. Given this set of quantum numbers, the parity and charge conjugation of the states are derived by $P = (-1)^{(L+1)}$ and $C = (-1)^{(L+S)}$. Figure 1 shows the mass and quantum number assignments of the well established charmonium states.

All the predicted states below open charm threshold have been observed, leaving the search open only to states above the threshold. In this field the latest developments concern the measurement of the paramaters and the quantum number assignment for the $J^{PC} = 1^{--}$ states.

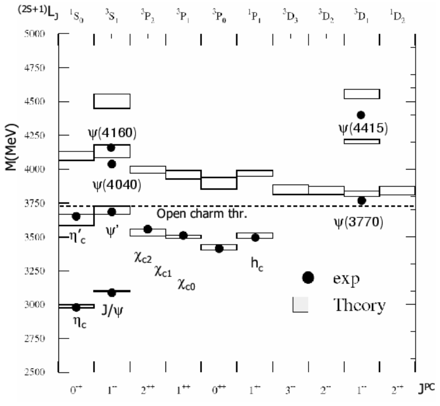


Figure 1: *Charmonium states with $L <= 2$. The theory predictions are according to the potential models described in Ref. [1].*

2. Non-standard charmonium states

2.1 The $X(3872)$

The $X(3872)$ was the first state that was found not to easily fit charmonium spectroscopy. It was initially observed decaying into $J/\psi\pi^+\pi^-$ with a mass just beyond the open charm threshold [2]. The $\pi^+\pi^-$ invariant mass distribution preferred the hypothesis of a $X(3872) \to J/\psi\rho$ decay, which would have indicated that if this were a charmonium state, the decay would have violated the isospin. Since it would be quite unusual to have the dominant decay to be isospin violating, a search of the isospin partner $X^+ \to J/\psi\rho$ was conducted invain by BaBar [3]. In the meanwhile BaBar had evidence of the decay $X \to J/\psi\gamma$ [4] and $X \to \psi(2S)\gamma$ [5], implying positive intrinsic charge conjugation. Finally, the best assessment of the J^{PC} of this particle comes form the CDF collaboration that performed the full angular analysis of the $X \to J/\psi\pi\pi$ decay [6] concluding that $J^{PC} = 1^{++}$ and 2^{-+} are the only assignments consistent with data. It also confirmed that the decays are consistent with a ρ as intermediate state.

Table 1: Measured $X(3872)$ branching fractions, separated by production and decay mechanism. The ratio of the measurements in the two production mechanisms is also reported as $R_{0/+} = BF(B \to XK^-)/BF(B \to XK^0)$. A '*' indicates numbers which are derived from the published values by assuming gaussian uncorrelated errors.

	BaBar	Belle	combined
BF($B \to XK^-$)BF($X \to J/\psi\pi\pi$)$\times 10^5$	$0.84 \pm 0.15 \pm 0.07$ [7]	$0.81 \pm 0.09 \pm 0.07$ [8]	$0.82 \pm 0.09^*$
BF($B \to XK^0$)BF($X \to J/\psi\pi\pi$)$\times 10^5$	$0.35 \pm 0.19 \pm 0.04$ [7]	$0.67 \pm 0.16 \pm 0.06$ [8]	$0.53 \pm 0.13^*$
BF($B \to XK^-$)BF($X \to D^{*0}D^0$)$\times 10^5$	$17 \pm 4 \pm 5$ [9]	$10.7 \pm 3.1^{+1.9}_{-3.3}$ [10]	$13 \pm 3^*$
BF($B \to XK^0$)BF($X \to D^{*0}D^0$)$\times 10^5$	$22 \pm 10 \pm 4$ [9]	$17 \pm 7^{+3}_{-5}$ [10]	$19 \pm 6^*$
$R_{0/+}$ with $X \to J/\psi\pi\pi$	0.41 ± 0.24 [7]	0.82 ± 0.22 [8]	$0.63 \pm 0.16^*$
$R_{0/+}$ with $X \to D^{*0}D^0$	1.4 ± 0.6 [9]	$1.6 \pm 0.6^*$	$1.5 \pm 0.4^*$

The most recent advances on this topics concern the measurement of the mass of the $X(3872)$ and the discussion on whether there is more than one state with similar mass (as predicted by tetraquark models) or not. The two options being investigates is that either the neutral and charged B mesons decay to different linear combinations of the two possible X states or that the two states decay into different final states (in particular $J/\psi\pi\pi$ and $D^{*0}D^0$). The first possibility (different B^0 and $B^\pm$ decays) has been investigated by CDF [11], where the $J/\psi\pi\pi$ spectrum has been fitted searching for evidence of multiple structures. The negative result of such a search has allowed to establish that the eventual two states would have a mass different smaller than 3.2 MeV at 90% C.L..

Both scenarios of multiple X states have instead been investigated by several measurements of mass of the X state performed by BaBar [7, 12] and Belle [8, 13] . The summary of all available mass measurements is shown in Fig. 2 where the measurements are separated by production and decay channel. There is an indication that the particle decaying into $J/\psi\pi\pi$ is different from the one decaying into $D^{*0}D^0$, their masses differing by about 3.5 standard deviations.

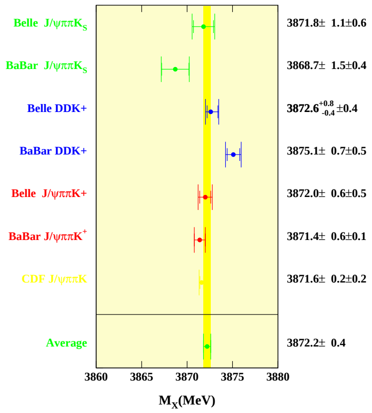


Figure 2: *Measured mass of the $X(3872)$ particle. The different production modes ($B^0 \to XK_S$ and $B^- \to XK^-$) and the different decay modes ($X \to J/\psi\pi\pi$ and $X \to D^{*0}D^0$) are separated.*

In addition, the BaBar paper contains also a first measurement of the $X(3872)$ width, $\Gamma = (3.0^{+1.9}_{-1.4} \pm 0.9)$MeV [12] . Finally the measurements of X the branching fractions in $J/\psi\pi\pi$ and $D^{*0}D^0$ are summarized in Tab. 1, together with the ratio between the two which is another possible discriminant among theoretical interpretations.

2.2 The 1^{--} family

The easiest way to assign a value for J^{PC} to a particle is to observe its production via e^+e^- annihilation, where the quantum numbers must be the same as the the photon: $J^{PC} = 1^{--}$. B factories can investigate a large range of masses for such particles by looking for events where the initial state radiation brings the e^+e^- center-of-mass energy down to the particle's mass (the so-called 'ISR' events). Alternatively, dedicated e^+e^- machines, like CESR and *BEP* scan directly the certer-of-mass energies of interest.

The observation of new states in these processes started with the discovery of the $Y(4260) \to J/\psi\pi^+\pi^-$ by BaBar [14], promptly confirmed both in the same production process [15] and in di-

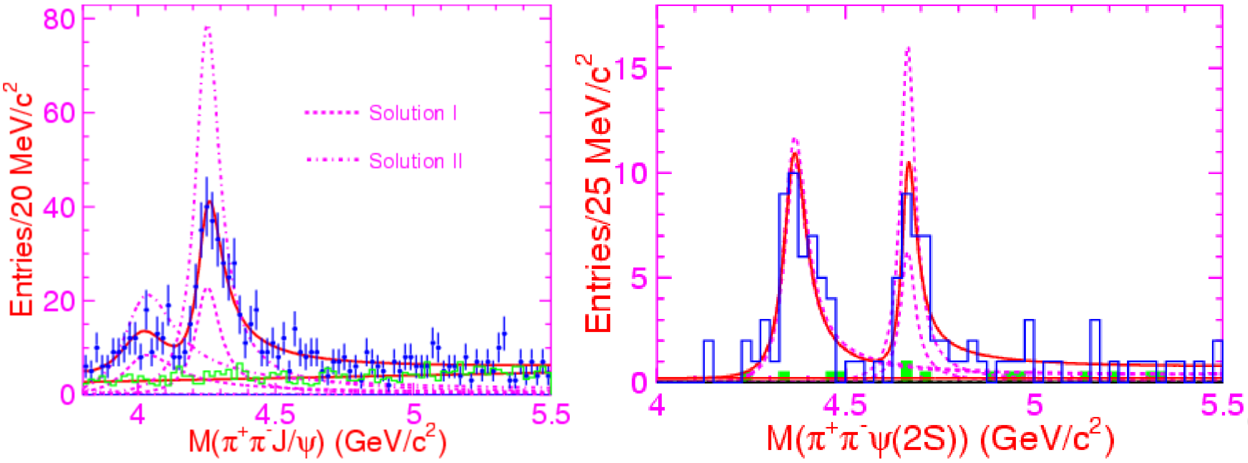


Figure 3: *$J/\psi\pi^+\pi^-$ (left) and $\psi(2S)\pi^+\pi^-$ (right) invariant mass in ISR production.*

rect production by CLEO-c [16]. The latter paper also reported evidence for $Y(4260) \to J/\psi\pi^0\pi^0$ and some events of $Y(4260) \to J/\psi K^+K^-$.

While investigating whether the $Y(4260)$ decayed to $\psi(2S)\pi^+\pi^-$ BaBar found that such decay did not exist but discovered a new 1^{--} state, the $Y(4350)$ [17]. While the absence of $Y(4260) \to \psi(2S)\pi^+\pi^-$ decays could be explained if the pion pair in the $J/\psi\pi^+\pi^-$ decay were produced with an intermediate state that is too massive to be produced with a $\psi(2S)$ (e.g. an f^0), the absence of $Y(4350) \to J/\psi\pi^+\pi^-$ is still to be understood, more statistics might be needed in case the $Y(4260)$ decay hides the $Y(4350)$.

Next, Belle has published the confirmation of all these 1^{--} states [18, 19] and at the same time has unveiled a new states that was not visible in BaBar data due to the limited statistics: the $Y(4660)$. Figure 3 shows the published invarianet mass spectra for both the $J/\psi\pi^+\pi^-$ and the $\psi(2S)\pi^+\pi^-$ decays.

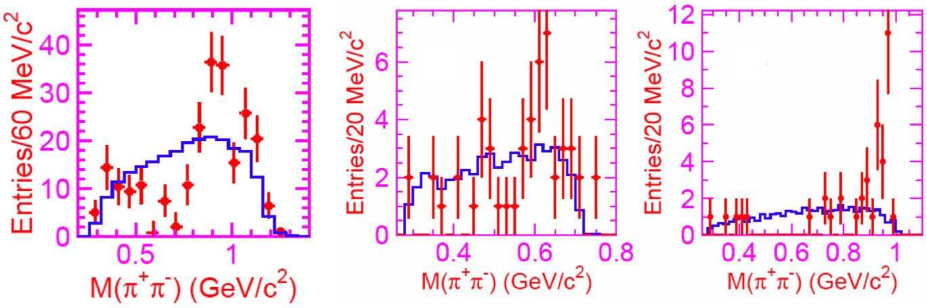


Figure 4: *Di-pion invariant mass distribution in $Y(4260) \to J/\psi\pi^+\pi^-$ (left), $Y(4350) \to \psi(2S)\pi^+\pi^-$ (center), and $Y(4660) \to \psi(2S)\pi^+\pi^-$ (right) decays.*

A critical information for the unravelling of the puzzle is whether the pion pair comes from a resonant state. Figure 4 shows the di-pion invariant mass spectra published by Belle for all the regions where new resonances have been observed. Although the subtraction of the continuum is missing, there is some indication that only the $Y(4660)$ has a well defined intermediate state (most likely an f_0), while others have a more complex structure.

A discriminant measurement between Charmonium states and new aggregation forms is the relative decay rate between these decays into Charmonium and the decays into two charm mesons. Searches have therefore been carried out for $Y \to D^{(*)}D^{(*)}$ decays [20, 21, 22] without any evidence for a signal. The most stringent limit is [22] $BF(Y(4260) \to D\overline{D})/BF(Y(4260) \to J/\psi\pi^+\pi^-) <$ 1.0@ 90% confidence level.

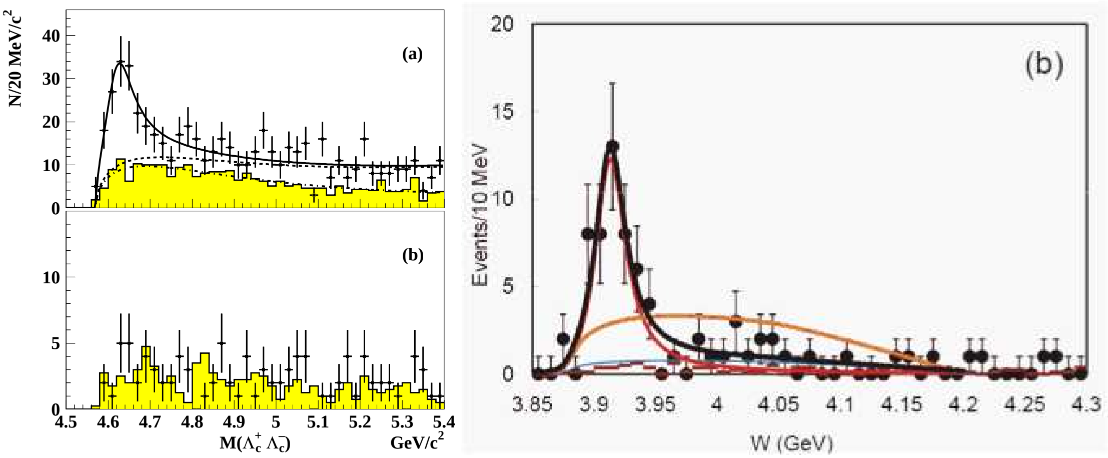


Figure 5: *The $\Lambda_c\overline{\Lambda}_c$ distribution in ISR (left) and the $J\psi\omega$ distribution in $\gamma\gamma$ events as measured by Belle. The superimposed lines are the result of the fits to the data whose results are reported in the text.*

A distinctive signature of tetraquarks would instead be the observation of decays of these mesons into two baryons. This has lead to the search by Belle of resonant structures decaying into $\Lambda_c\overline{\Lambda}_c$ associated to ISR [23]. A tantalizing structure appears near threshold (see Fig. 5, which fitted with a Breit-Wigner returns $M = (4634^{+8+5}_{-7-8})$ Mev and $\Gamma_{tot} = (92^{+40+10}_{-24-12})$ MeV , properties which are close to the one of the $Y(4660)$.

2.3 The 3940 family

Three different states have been observed in the past years by the Belle collaboration with masses close to 3940Mev/c^2: one, named X, observed in continuum events (i.e. not in $Y(4S)$ decays) produced in pair with a J/ψ meson and decaying into DD^* [24]; a second one, named Y, observed in B decays and decaying into $J/\psi\omega$ [25]; a third one, named Z produced in two-photon reactions and decaying into D-pairs [26]. While the X is consistent with both $J^{PC} = 0^{+-}$ and 1^{++}, the quantum number assignment of the Y and the Z states is clear: $J^{PC} = 1^{++}$ and 2^{++} respectively. Finally the Y is the only apparently broad state ($\Gamma = 87 \pm 34$MeV).

Because of these quantum number assignments and their masses these states are good candidates for the radial eccitation of the χ mesons, in particular the $Z(3940)$ meson could be identified with the $\chi_{c0}(2P)$ and the $Y(3940)$ with the $\chi_{c1}(2P)$. The unclear points are the identification of the $X(3940)$ state and the explanation of why the $Y(3940)$ state does not decay preferentially in D mesons.

Next, the BaBar collaboration confirmed the $Y(3940) \to J/\psi\omega$ decays [27], but measuring a lower mass and a width, albeit consistent ($m_Y = 3914.6^{+3.8}_{-3.4}(stat.) \pm 1.9(sys.)\mathrm{Mev}/c^2$, $\Gamma_Y = 33^{+12}_{-8}(stat.) \pm 5(sys.)\mathrm{MeV}$). While the experimental differences among the two measurements are still under investigation, a new study has observed a state which is consistent with the parameters as measured by BaBar: the Belle spectrum of the $J/\psi\omega$ invariant mass in $\gamma\gamma$ events, shown in Fig. 5 has a structure with $m_Y = 3914.6^{+3.8}_{-3.4}(stat.) \pm 1.9(sys.)\mathrm{Mev}/c^2$, $\Gamma_Y = 33^{+12}_{-8}(stat.) \pm 5(sys.)\mathrm{MeV}$ [28].

2.4 The charged states

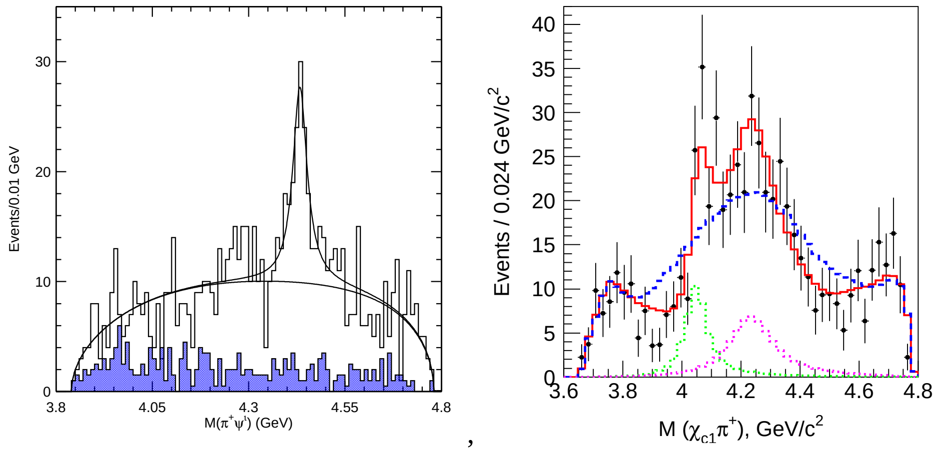
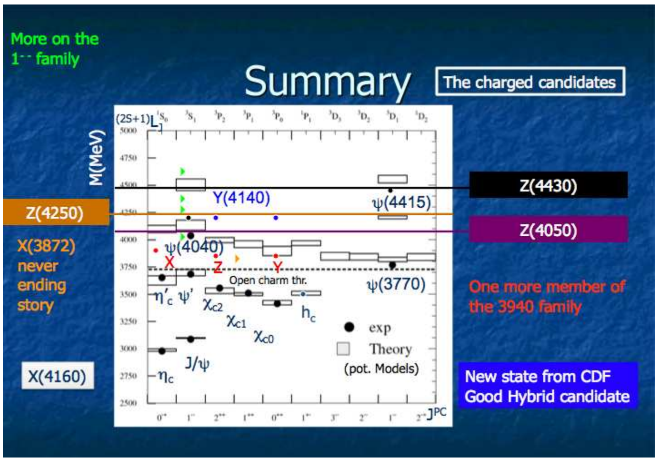


Figure 6: *The $\psi(2S)\pi^{\pm}$ (left) and $\chi_{c1}\pi^{\pm}$ (right) invariant mass distributions superimposed with the fit result showing the three charged resonances.*

The real turning point in the query for states beyond the Charmonium was the observation of charge states decaying into charmonium. There is in fact no way to explain such observation without having at least four bound quarks ($c\bar{c}u\bar{d}$). There is currently evidence of three charged states, all seen exclusively by the Belle Collaboration: the $Z(4430)$ state decaying into $\psi(2S)\pi^{\pm}$ [29], and the Z_1 and Z_2 states decaying into $\chi_{c1}(2S)\pi^{\pm}$ [30].

Unfortunately these states have been observed in B decays in association with a charged kaon, i.e. in three body $B \to X_{cc}\pi K$ decays, where $X_{cc} = \psi(2S)$ or χ_{c1}. Three body decays suffer from interferences between strong amplitudes mediated by different resonances. In these particular cases the πK system presents several known resonances that could cause significant effects of reflection. Namely, the decays $B \to X_{cc}K^*(892)$, $B \to X_{cc}K^*(1410)$, and in particular their interference constitute irreducible sources of background which are difficult to estimate. The original observation of the $Z(4430)$ [29] has been therefore object of detailed scrutiny by the BaBar collaboration who performed the search for the same final state by studying in detail the efficiency corrections and the shape of the background taking the latter from the data as much as possible [31]. The search resulted into hints of a structure close to Belle's observation, but after accurate estimate of the background results into an exclusion on the product of branching fractions $\mathrm{BF}(B \to Z(4330)K^+)\mathrm{BF}(Z(4330) \to \psi(2S)\pi) < 3.110^{-5}$@95% C.L. to be compared with $\mathrm{BF}(B \to Z(4330)K^+)\mathrm{BF}(Z(4330) \to \psi(2S)\pi) = 4.1^{+1.0}_{-1.4}10^{-5}$ as reported in Ref. [29]. Above all the paper from BaBar has raised the attention to the problems inherent to the analysis of the Dalitz plot, leading from a reanalysis from Belle [32].

The result of this analysis, which confirm the conclusions of the original analysis although the errors on the parameters increase significantly, and of the $B \to \chi_{c1}\pi K$ decays (not yet analyzed with the full three body approach) are shown in Fig. 6. The fits to the $\psi(2S)\pi$ and $\chi_{c1}\pi$ invariant mass distributions return masses $M = 4443^{+24}_{-18}\mathrm{MeV/c^2}$, $M = 4051 \pm 14^{+20}_{-41}\mathrm{MeV/c^2}$, and $M = 4248^{+44+180}_{-29-35}\mathrm{MeV/c^2}$, and widths $\Gamma = 109^{+113}_{-71}$ MeV, $\Gamma = 82^{+21+47}_{-17-22}\mathrm{MeV/c^2}$, and $\Gamma = 177^{+54+316}_{-39-61}\mathrm{MeV/c^2}$ for the $Z(4430)$, Z_1, and Z_2 states respectively.



More on the 1-- family

Summary

The charged candidates

Z(4250)

X(3872) never ending story

X(4160)

Z(4430)

Z(4050)

One more member of the 3940 family

New state from CDF Good Hybrid candidate

Figure 7: *Measured masses of the newly observed states, positioned in the spectroscopy according to their most likely quantum numbers. The charged state ($Z(4430)$) has clearly no C quantum number.*

Finding the corresponding neutral state, observing a decay mode of the same states or at least having a confirmation of their existence, are critical before a complete picture can be drawn.

2.5 The $Y(4140)$

The latest report of a new exotic state comes from CDF, who has observed an enhancement close to the threshold in the $J/\psi\phi$ invariant mass in $B \to J/\psi\phi K$ decays [33]. The fitted mass of the resonant state is $M = (4143.0 \pm 2.9 \pm 1.2)$ MeV with $\Gamma = (11.7^{+8.3}_{5} \pm 3.7)$ MeV. While the most basic quantum numbers assignment would be $J^{PC} = 0^{++}$, $J^{PC} = 1^{-+}$ is also allowed, leaving open the possibility of this state being the lowest lying hybrid. This hypothesis is also suggested by the closeness of the measured mass with the predictions of lattice calculations for the hybrid ground state (see for instance Ref. [34]).

3. Conclusions

More than 40 years after its first formulation, the quark model is still open to new observations. In particular the heavy-quarkonium is still a valid test ground for understanding QCD. The study of well established quarkonium states yields information on low energy QCD while the undestanding of the quarkonium spectroscopy, predictable in potential models, allows searches for different aggregation states than the long established mesons.

The high statistics and quality data from B-Factories have produced a very large number of new states whose interpretation is still a matter of debate. This paper attempted a categorized review of all these states. A full summary, including the most likely quantum number assignment is shown in Fig. 7. Lots of theoretical models have been developed to interpret the situation but the picture is far from complete: more precise predictions are needed from theory and a systematic experimental exploration of all possibile production and decay mechanisms of these new states is still in the works.

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