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Heavy Quarkonium Spectroscopy

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I. INTRODUCTION

Although the Standard Model of elementary particles is well established, strong interactions are not yet fully under control. We believe QCD is the field theory capable of describing them, but we are not yet capable, in most of the cases, to make exact predictions. Systems that include heavy quark-antiquark pairs (quarkonia) are ideal and unique laboratories to proble both the high energy regimes of QCD, where an expansion in terms of the coupling constant is possible, and the low energy regimes, where non-perturbative effects dominate.

In the last years this field is experiencing a rapid expansion with a wealth of new data coming in from diverse sources: data on quarkonium formation from dedicated experiments (BES at BEPC, KEDR at VEPP-4M CLEO-c at CESR), clear samples produced by high luminosity B-factories (PEP and KEKB), and very large samples produced from gluon-gluon fusion in $p\bar{p}$ annihilations at Tevatron (CDF and D0 experiments).
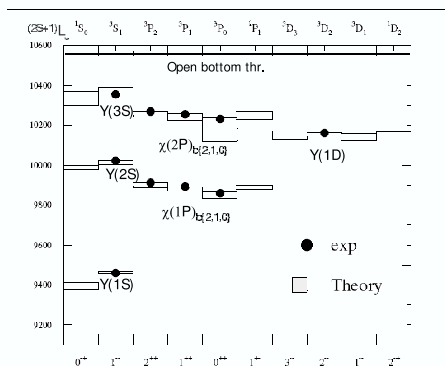

FIG. 1: *Charmonium states with $L <= 2$. The theory predictions are according to the potential models described in Ref. [1].*

In this review I will first summarize recent developments in the understanding of heavy quarkonium states which have a well established quark content.

Next, the core of the paper will be spent to review the experimental evidences of new states that might be aggregations of more than just a quark-antiquark pair. Although the possibility to have bound states of two quarks and two antiquarks or of quark-antiquark pairs and glu-
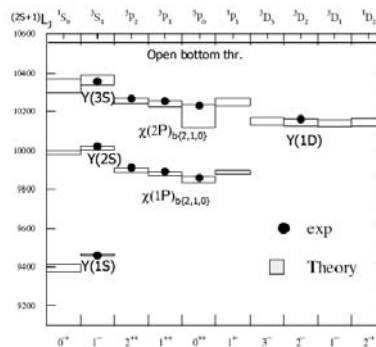

FIG. 2: *Bottomonium (right) with $L <= 2$. The theory predictions are according to the potential models described in Ref. [1].*

ons has been predicted since the very start of the quark model [2], no observed state has yet been attributed to one of them: achieving such an attribution would be a major step in the understanding of the strong interactions.

The currently most credited 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. While this could be the case for when $Q = b$, this does not apply for $Q = c$, where most of the current experimental data are. 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.

TABLE I: Most recent determination of the $J^{PC} = 1^{--}$ charmonium states from BES [3], compared to the 2006 edition of the PDG [4]

		$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M	PDG2006	3771.1±2.4	4039±1.0	4153±3	4421±4
(MeV/c^2)	BES '07	3771.4±1.8	4038.5±4.6	4191.6±6.0	4415.2±7.5
Γ_{tot}	PDG2006	23.0±2.7	80±10	103±8	62±20
(MeV)	BES '07	25.4±6.5	81.2±14.4	72.7±15.1	73.3±21.2

- 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. a large amount of states is 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 will summarize the latest findings on the spectroscopy of the known heavy quarkonium states and the status of the art of the understanding of all other states which might not fit in the ordinary spectroscopy.

II. HEAVY QUARKONIUM 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 $C = (-1)^{(L+S)}$. Figures 1 and 2 show the mass and quantum number assignments of the well established charmonium and bottomonium states.

A. Charmonium spectroscopy

Figure 1 shows that 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.

The BES collaboration has recently performed a fit to the R scan results which takes into account interference between resonances more accurately [3]. The updated parameters are reported in Tab. I, compared with the most recent determinations.

The $J^{PC} = 1^{--}$ assignment does not univocously identify the state, since both $^{2S+1}L_J = ^3D_1$ and $^3D_1$ states

would match it. The recent observation from Belle of the first exclusive decay of the $\psi(4415) \to DD_2^*(2460)$ [5], shows that this meson is predominantly D wave. At the same time the study from CLEO-c of the $\psi(3770) \to \chi_{cJ}\gamma$ [6] confirms the dominance of the D wave also in this meson. Both these assignments confirm the theoretical predictions as shown in Fig. 1.

B. Bottomonium transitions

Figure 2 shows that the panorama in the bottomonium sector is much less complete, since there is a large number of states below the open bottom threshold which have not yet been observed. Moreover there is no recent measurement on the topic.
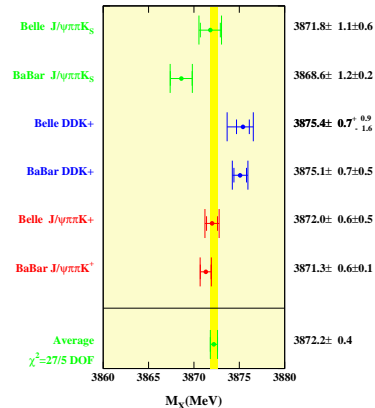

FIG. 3: *Measured mass of the $X(3872)$ particle. The different production modes ($B^0 \to XK_S$ and $B^- \to XK^-$) and the different decay modes ($X \to J/\psi\pi\pi$ and $X \to D^{*0}D^0$) are separated.*

There are, on the contrary, plenty of results on the transitions between $J^{PC} = 1^{--}$ states, i.e. between $Y(nS)$ and $Y(mS)$ states. These transitions are relevant because it is possible to predict both the di-pion invariant mass spectrum in the case of $Y(nS) \to Y(mS)\pi^+\pi^-$ decays, and the relative rate between these decays and the $Y(nS) \to Y(mS)\eta$ decays. These transitions allow therefore stringent tests of low energy QCD, in particular of the prediciton of the Multipole Expansion [7].

Recent measurements of the $Y(4S) \rightarrow Y(2S)\pi^+\pi^-$ decays from BaBar [8] showed a discrepancy with the above-mentioned predictions. Since such predictions mutuated the matrix elements from PCAC, CLEO-c recently published a comprehensive study of $Y(3S) \rightarrow Y(mS)\pi^+\pi^-$ decays under more general assumpions [9]: a fit to the two distributions ($m = 1, 2$) letting the matrix elements float shows a good agreement with the data, thus confirming the validity of the model.

III. NON-STANDARD CHARMONIUM STATES

A. 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 [10]. The $\pi^+\pi^-$ invariant mass distribution preferred the hypothesis of a $X(3872) \rightarrow J/\psi\rho$ 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 $X^+ \rightarrow J/\psi\rho$ was conducted invain by BaBar [11]. In the meanwhile the decay $X \rightarrow J/\psi\gamma$ was observed [12], implying positive intrinsic charge conjugation.

The most recent developments concern the final assessment of the J^{PC} of this particle and the indication that the $X(3872)$ is a actually a doublet. The CDF collaboration has infact performed the full angular analysis of the $X \rightarrow J/\psi\pi\pi$ decay [13] concluding that $J^{PC} = 1^{++}$ and 2^{-+} are the only assignments consistent with data. It also confirmed that the decays has a ρ as intermediate state. Combining this information with the preliminary result from Belle [14] which rules out the 2^{-+} hypothesis, the only possible assignment is $J^{PC} = 1^{++}$.

As far as the mass and width of the $X(3872)$ are concerned, BaBar has published an analysis of the $B \rightarrow XK$ decays with $X \rightarrow D^{*0}D^0$ [16] while Belle has updated the mass measurements in $X \rightarrow J/\psi\pi\pi$ decays [18]. The summary of all available mass measurements is shown in Fig. 3 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 4.5 standard deviations.

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. Finally the measurements of X the branching fractions in $J/\psi\pi\pi$ and $D^{*0}D^0$ are summarized in Tab. II.

B. 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.
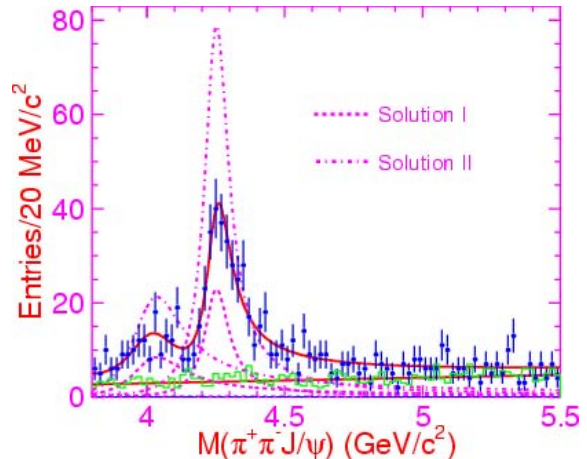

FIG. 4: $J/\psi\pi^+\pi^-$ invariant mass in ISR production.
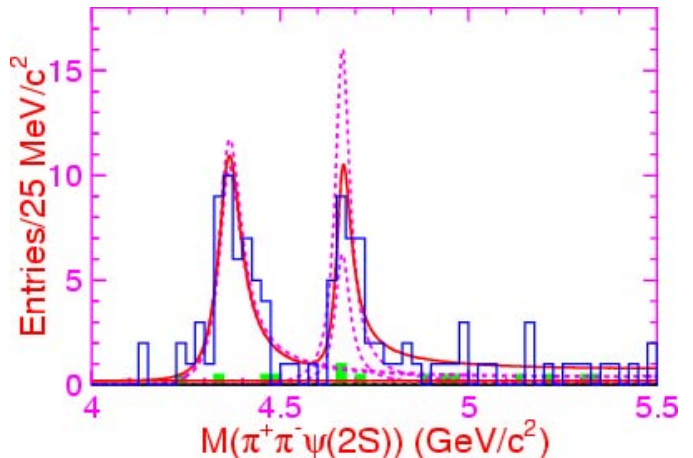

FIG. 5: $\psi(2S)\pi^+\pi^-$ invariant mass in ISR production.

The observation of new states in these processes started with the discovery of the $Y(4260) \rightarrow J/\psi\pi^+\pi^-$ by BaBar [19], promptly confirmed both in the same production process [20] and in direct production by CLEO-c [21]. The latter paper also reported evidence for $Y(4260) \rightarrow J/\psi\pi^0\pi^0$ and some events of $Y(4260) \rightarrow J/\psi K^+K^-$.

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 $Y(4350)$ [22]. While the absence of $Y(4260) \rightarrow \psi(2S)\pi^+\pi^-$ decays could be explained if the pion pair in the $J/\psi\pi^+\pi^-$ decay were

TABLE II: 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
$\mathrm{BF}(B \to XK^-)\mathrm{BF}(X \to J/\psi\pi\pi)\times10^5$	$1.01\pm0.25 \pm 0.10$ [15]	1.05 ± 0.18 [10]	$1.04\pm0.15^*$
$\mathrm{BF}(B \to XK^0)\mathrm{BF}(X \to J/\psi\pi\pi)\times10^5$	$0.51\pm0.28 \pm 0.07$ [15]	$0.99 \pm 0.33^*$	$0.72 \pm 0.22^*$
$\mathrm{BF}(B \to XK^-)\mathrm{BF}(X \to D^{*0}D^0)\times10^5$	$17 \pm 4 \pm 5$ [16]	$10.7\pm3.1^{+1.9}_{-3.3}$ [17]	$13 \pm 3^*$
$\mathrm{BF}(B \to XK^0)\mathrm{BF}(X \to D^{*0}D^0)\times10^5$	$22 \pm 10 \pm 4$ [16]	$17\pm7^{+3}_{-5}$ [17]	$19 \pm 6^*$
$R_{0/+}$ with $X \to J/\psi\pi\pi$		0.50 ± 0.30 [15]	0.94 ± 0.26	$0.75 \pm 0.20^*$
$R_{0/+}$ with $X \to D^{*0}D^0$		1.4 ± 0.6 [16]	$1.6 \pm 0.6^*$	$1.5 \pm 0.4^*$

produced with an intermediate state that is to amssive 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 $Y(4350)$.

Recently Belle has published the confirmation of all these 1^{--} states [23, 24] and at the same time has unveiled a new states that was not visible in BaBar data due to the limited statistics: the $Y(4660)$. Figures 4 and 5 show the published invarianet mass spectra for both the $J/\psi\pi^+\pi^-$ and the $\psi(2S)\pi^+\pi^-$ decays.

A critical information for the unravelling of the puzzle is whether the pion pair comes from a resonant state. Figure 6 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 [25–27] without any evidence for a signal. The most stringent limit is [27] $BF(Y(4260) \to D\bar{D})/BF(Y(4260) \to J/\psi\pi^+\pi^-) < 1.0@\ 90\%$ confidence level.

C.   The 3940 family

Three different states have been observed in the past years by the Belle collaboration with masses close to $3940\mathrm{Mev}/c^2$: 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^* [28]; a second one, named Y, observed in B decays and decaying into $J/\psi\omega$ [29]; a third one, named Z produced in two-photon reactions and decaying into D-pairs [30]. 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 ($\Gamma = 87 \pm 34\mathrm{MeV}$).

Because of these quantum number assignments and their masses these states are good candidates for the ra-dial 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.

The most recent devdelpment on this topic is the confirmation from the BaBar collaboration of the $Y(3940) \to J/\psi\omega$ decays [31]. The analysis utilizes the decay properties of the ω meson to extract a clean signal (see Fig. 7). The interesting part is that he mass and the width measured in this paper are lower than when observed, albeit consitent ($m_Y = 3914.6^{+3.8}_{-3.4}(stat.) \pm 1.9(sys.)\mathrm{Mev}/c^2$, $\Gamma_Y = 33^{+12}_{-8}(stat.) \pm 5(sys.)\mathrm{MeV}$), opens the interesting possibility that the X and the Y particles be the same, thus solving the two abovementioned open issues.

D.   The $X(4160)$

As we have already discussed, it is critical to investigate decay channels of the new states into D meson pairs. Unfortunately the detection efficiency for D mesons in low, due to the large number of possible decays. The Belle collaboration has developed a partial reconstruction technique that allows to overcome this limitation in the case of new states produced in continuum paired with known Charmonium states [32]. The Charmonium is fully reconstructed, while only one of the two D mesons is reconstructed. The kinematics of the other is inferred from the known center-of-mass energy and the different possibile D mesons are discriminated on the basis of the missing mass.

This technique has allowed the confirmation of the $X(3940)$ production and decay, and, most interestingly, the observation of the $X(4160)$ state, decaying into DD^*. Given the fact that, for reasons yet to be understood, continuum events seem to produce $J^{PC} = 0^{-+}$ or 1^{++} states in pair with the J/ψ and since the measured mass is consistent with the expectations of a radial excitation of the η_c, this new state is likely to be an $\eta_c(3S)$.
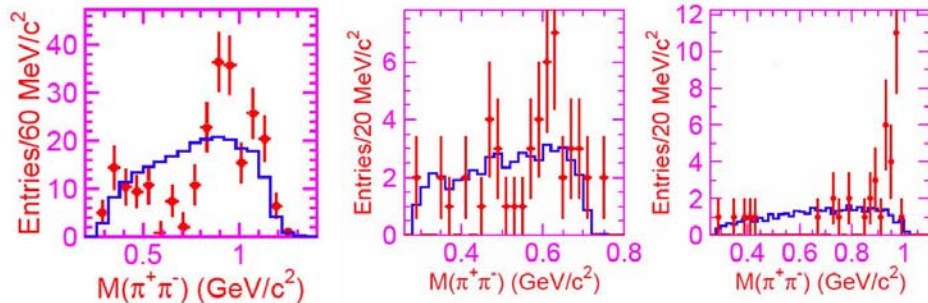
FIG. 6: *Di-pion invariant mass distribution in* $Y(4260) \to J/\psi\pi^+\pi^-$ *(left),* $Y(4350) \to \psi(2S)\pi^+\pi^-$ *(center), and* $Y(4660) \to \psi(2S)\pi^+\pi^-$ *(right) decays.*
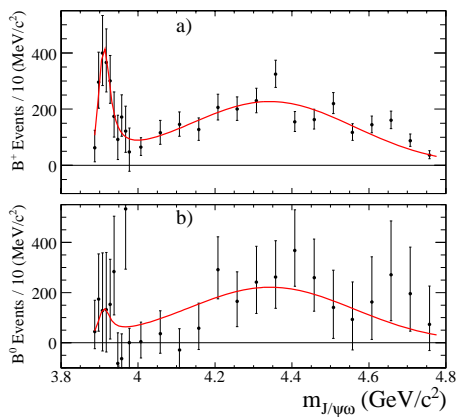

FIG. 7: *The* $J/\psi\omega$ *distribution in a)* $B \to J/\psi\omega K^+$ *and b)* $B \to J/\psi\omega K_S$ *decays. The superimposed line is the result of the fit to the data.*
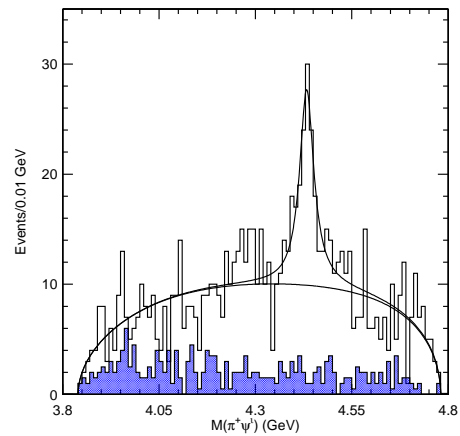

FIG. 8: *The* $\psi(2S)\pi$ *invariant mass distribution in* $B \to \psi(2S)\pi K$ *decays.*

E.   The first charged state: $Z(4430)$

The real turning point in the query for states beyond the Charmonium was the observation by the Belle Collaboration of a charged state decaying into $\psi(2S)\pi^\pm$ [33]. Figure 8 shows the fit to the $\psi(2S)\pi$ invariant mass distribution in $B \to \psi(2S)\pi K$ decays, returning a mass $M = 4433 \pm 4\text{MeV/c}^2$ and a width $\Gamma = 44^{+17}_{-13}$ MeV. Due to the relevance of such an observation a large number of tests has been performed, breaking the sample in several subsamples and finding consistent results in all cases. Also, the possibility of a reflection of a $B \to \psi(2S)K^**$ decay has been falsified by explicitly vetoing windows in the $K\pi$ invariant mass.

In terms of quarks, such a state must contain a c and a $\bar{c}$, but given its charge it must also contain at least a u and a $\bar{d}$. The only open options are the tetraquark, the molecule or the threshold effects. The latter two options

are possible due to the closeness of the $D_1 D^*$ threshold.

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

IV.   CONCLUSIONS

More than 30 years after its first observation, 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
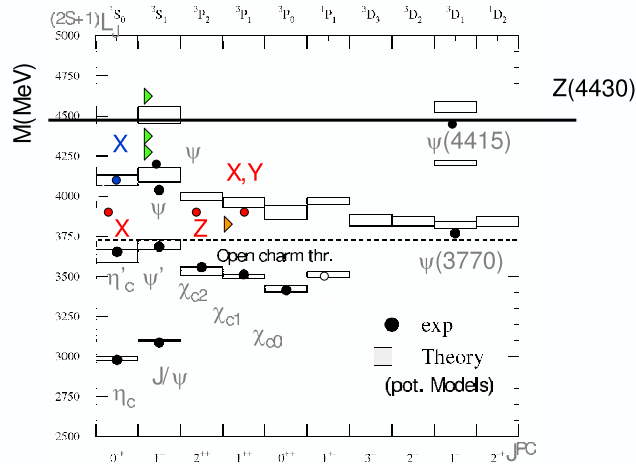
FIG. 9: *Measured masses of the newly observed states, positioned in the spectroscopy according to their most likely quantum numbers. The charged state (Z(4430)) has clearly no C quantum number.*

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. 9. 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.

V. ACKNOWLEDMENTS

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