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New exotic charmonium states*

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Abstract In the last years many states in the charmonium mass region were discovery by BABAR, Belle and CDF collaborations. I discuss some of these discoveries, and how the QCD Sum Rule approach can be used to understand the structure of these states.

Key words non-perturbative methods, heavy mesons spectroscopy, exotic mesons

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1 Introduction

In the recent years, many new states were observed by BABAR, Belle and CDF collaborations, like the X(3872) [1], Y(3930) [2], Z_1^+(4050) [3], Y(4140) [4], Z_2^+(4250) [3], Y(4260) [5], Y(4360) [6], Z^+(4430) [7] and Y(4660) [8]. All these states were observed in decays containing a J/ψ or ψ′ in the final states and their masses are in the charmonium region. Therefore, they certainly contain a $c\bar{c}$ pair in there constituents. Although they are above the threshold for a decay into a pair of open charm mesons they decay into J/ψ or ψ′ plus pions, which is unusual for $c\bar{c}$ states. Another common feature of these states is the fact that their masses and decay modes are not in agreement with the predictions from potential models. For these reasons they are considered as candidates for exotic states. Exotic states are states with a more complex structure than the simple quark-antiquark state, like hybrid, molecular or tetraquark states. The idea of unconventional quark structures is quite old and the light scalar mesons were the first candidates for tetraquark exotic states. However, despite decades of progress, no exotic meson has been conclusively identified. In particular, those with $q\bar{q}$ quantum numbers, like the light scalars, should mix with ordinary mesons and are thus hard to understand. Therefore, the observation of these new states provide a challenge to our understanding of QCD.

In the next sections I discuss how the QCD sum rule (QCDSR) approach can be used to interpret the structure of some of these states [9].

2 QCD sum rules

The method of the QCDSR was first introduced, 30 years ago, by Shifman, Vainshtein and Zakharov [10] and applied to the mesons. They demonstrated that the non-perturbative power corrections are more important than the strong coupling, α_s, corrections. The non-perturbative power corrections come about through a series expansion of operators. As the dimension of the operators increase, the power of the momentum transfer, Q^2, in the denominator of the terms also increases, giving a series in $1/Q^2$. The sum rule method was latter extended to baryons by Ioffe [11] and Chung et al.[12]. Since then the QCDSR technique has been applied to study numerous hadronic properties with various flavor content and is discussed in many reviews [13–15] emphasizing different aspects of the method.

The idea of the QCDSR formalism is to approach the bound state problem in QCD from short distances, where the dynamics is essentially perturbative, and move to larger distances including non-perturbative effects “step by step”, and using some approximate procedure to extract information on hadronic properties. The fundamental assumption of the QCDSR approach is the principle of duality: it is assumed that there is an interval over which a hadron may be equivalently described at both, the quark level and at the hadron level. Therefore, the

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correlation function:

$$\Pi(q)\equiv \mathrm{i}\int \mathrm{d}^4x\,\mathrm{e}^{\mathrm{i}q\cdot x}\langle 0|T[j(x)j^\dagger(0)]|0\rangle \ , \tag{1}$$

is evaluated in two different ways: at the quark level in terms of quark and gluon fields and at the hadronic level introducing hadron characteristics such as the mass and the coupling of the hadronic state to the current $j(x)$, which has the quantum numbers of the hadron we want to study.

At the quark level we employ the Wilson's operator product expansion (OPE). Therefore, the correlation function in Eq. (1) is written in a series of local operators:

$$\Pi^{\mathrm{OPE}}(q)=\sum_n C_n(Q^2)\hat{O}_n \ , \tag{2}$$

where the set $\{\hat{O}_n\}$ includes all local gauge invariant operators expressible in terms of the gluon fields and the fields of light quarks. The contributions of higher dimension condensates are suppressed by large powers of $\Lambda^2_{\mathrm{QCD}}/Q^2$, where $1/\Lambda_{\mathrm{QCD}}$ is the typical long-distance scale. Therefore, even at intermediate values of Q^2 ($\sim 1\ \ \mathrm{GeV}^2$), the expansion in Eq. (2) can be safely truncated after a few terms.

The calculation of the phenomenological side at the hadron level proceeds by writing a dispersion relation to the correlator in Eq. (1):

$$\Pi^{\mathrm{phen}}(q^2)=-\int \mathrm{d}s\,\frac{\rho(s)}{q^2-s+\mathrm{i}\epsilon}+\cdots \ , \tag{3}$$

where ρ is the spectral density given by the absorptive part of the correlator and the dots represent subtraction terms.

Since the current j ($j^\dagger$) is an operator that annihilates (creates) all hadronic states that have the same quantum numbers as j, $\Pi(q)$ contains information about all these hadronic states, including the low mass hadron of interest. In order for the QCDSR technique to be useful, one must parameterize $\rho(s)$ with a small number of parameters. In general one parameterizes the spectral density as a single sharp pole representing the lowest resonance of mass m, plus a smooth continuum representing higher mass states:

$$\rho(s)=\lambda^2\delta(s-m^2)+\rho_{\mathrm{cont}}(s)\,, \tag{4}$$

where λ gives the coupling of the current with the low mass hadron, H: $\langle 0|j|H\rangle=\lambda$.

In the QCDSR approach one assumes that the continuum contribution to the spectral density, $\rho_{\mathrm{cont}}(s)$ in Eq. (4), vanishes bellow a certain continuum threshold s_0. Above this threshold one uses the ansatz

$$\rho_{\mathrm{cont}}(s)=\rho^{\mathrm{OPE}}(s)\Theta(s-s_0)\,, \tag{5}$$

where

$$\rho^{\mathrm{OPE}}(s)=\frac{1}{\pi}\mathrm{Im}[\Pi^{\mathrm{OPE}}(s)]\,. \tag{6}$$

To improve the matching of the two descriptions of the correlator one applies the Borel transformation. The Borel transformation removes the subtraction terms in the dispersion relation, and exponentially suppresses the contribution from excited resonances and continuum states in the phenomenological side. In the OPE side the Borel transformation suppresses the contribution from higher dimension condensates by a factorial term.

After making a Borel transform on both sides of the sum rule, and transferring the continuum contribution to the OPE side, the sum rule can be written as

$$\lambda^2\mathrm{e}^{-m^2/M^2}=\int_{s_{\min}}^{s_0}\mathrm{d}s\,\mathrm{e}^{-s/M^2}\,\rho^{\mathrm{OPE}}(s)\,. \tag{7}$$

If both sides of the sum rule were calculated to arbitrary high accuracy, the matching would be independent of M^2. In practice, however, one has to find a range of M^2, called Borel window, in which the two sides have a good overlap and information on the lowest resonance can be extracted. To determine the allowed Borel window, one analyses the OPE convergence and the pole contribution: the minimum value of the Borel mass is fixed by considering the convergence of the OPE, and the maximum value of the Borel mass is determined by imposing the condition that the pole contribution must be bigger than the continuum contribution.

To extract the mass m one takes the derivative of Eq. (7) with respect to $1/M^2$, and divide the result by Eq. (7):

$$m^2=\frac{\displaystyle\int_{s_{\min}}^{s_0}\mathrm{d}s\,\mathrm{e}^{-s/M^2}\,s\,\rho^{\mathrm{OPE}}(s)}{\displaystyle\int_{s_{\min}}^{s_0}\mathrm{d}s\,\mathrm{e}^{-s/M^2}\,\rho^{\mathrm{OPE}}(s)}\,. \tag{8}$$

This quantity has the advantage to be less sensitive to the perturbative radiative corrections than the individual sum rules.

3 X(3872)

The X(3872) was first observed by Belle collaboration in the decay $\mathrm{B}^+\rightarrow \mathrm{X}(3872)\mathrm{K}^+\rightarrow \mathrm{J}/\psi\pi^+\pi^-\mathrm{K}^+$ [1], and was confirmed by CDF, D0 and BABAR [16]. The current world average mass is

$$M_{\mathrm{X}}=(3871.4\pm 0.6)\ \mathrm{MeV}\,, \tag{9}$$

and its total width is less than 2.3 MeV.

Studies from Belle and CDF that combine angular information and kinematic properties of the $\pi^+\pi^-$ pair, shows that only the hypotheses $J^{PC}=1^{++}$ and 2^{-+} are compatible with data. However, the possibility 2^{-+} is disfavored by the observation of the decay into $\psi(2S)\gamma$ and also by the observation of the decays into $D^0\bar{D}^0\pi^0$ by Belle and BABAR collaborations. Therefore, in the following we will asume the quantum numbers of the X(3872) to be 1^{++}.

Calculations using constituent quark models give masses for possible charmonium states, with $J^{PC}=1^{++}$ quantum numbers, which are much bigger than the observed X(3872) mass: $2\ ^3P_1(3990)$ and $3\ ^3P_1(4290)$ [17]. Another point against the assignement of the $c\bar{c}$ structure for X(3872) is the observation, by Belle [18], of the decay $X(3872)\to J/\psi\,\pi^+\pi^-\pi^0$ at a rate comparable to that of $X(3872)\to J/\psi\pi^+\pi^-$:

$$\frac{X\to J/\psi\,\pi^+\pi^-\pi^0}{X\to J/\psi\pi^+\pi^-}=1.0\pm0.4\pm0.3\ . \tag{10}$$

This observation establishes strong isospin and G parity violation, which is incompatible with a $c\bar{c}$ structure for X(3872).

The observation of these two decays, plus the coincidence between the X mass and the $D^{*0}D^0$ threshold: $M(D^{*0}D^0)=(3871.81\pm0.36)$ MeV [19], inspired the proposal that the X(3872) could be a molecular $(D^{*0}\bar{D}^0+\bar{D}^{*0}D^0)$ bound state with small binding energy [20, 21]. The $D^{*0}\bar{D}^0$ molecule is not an isospin eigenstate and the rate in Eq. (10) is explained in a very natural way in this model.

Other interesting possible interpration for the X(3872), first proposed by Maiani et al. [22], is that it could be a tetraquark state resulting from the binding of a diquark and a antidiquark.

3.1 QCDSR studies for X(3872)

Considering the X(3872) as a $J^{PC}=1^{++}$ state we can construct a current based on diquarks, as proposed in Ref. [22], and also a $D\bar{D}^*$ molecular current. The corresponding lowest-dimension interpolating operators are:

$$j_\mu^{(q,di)}=\frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}\left[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T)+(q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)\right], \tag{11}$$

for a tetraquark current, and

$$j_\mu^{(q,mol)}(x)=\frac{1}{\sqrt{2}}\bigg[\left(\bar{q}_a(x)\gamma_5 c_a(x)\bar{c}_b(x)\gamma_\mu q_b(x)\right)-\left(\bar{q}_a(x)\gamma_\mu c_a(x)\bar{c}_b(x)\gamma_5 q_b(x)\right)\bigg], \tag{12}$$

for a molecular $D\bar{D}^*$ current. In Eqs. (11) and (12), q denotes a u or d quark.

The two currents in Eqs. (11) and (12) were used, in Refs. [23] and [24] respectively, to study the X(3872). In both cases it was possible to find a Borel window where the pole contribution is bigger than the continuum contribution and with a reasonable OPE convergence. In the OPE side, the calculations were done at leading order in α_s and contributions of condensates up to dimension eight were included.

As an example for the determination of the Borel range we show the relative contribution of each term on the OPE expansion of the sum rule, in Fig. 1, and the comparison between pole and continuum contributions, in Fig. 2, for the case of the current in Eq. (11). These figures were taken from Ref. [23].

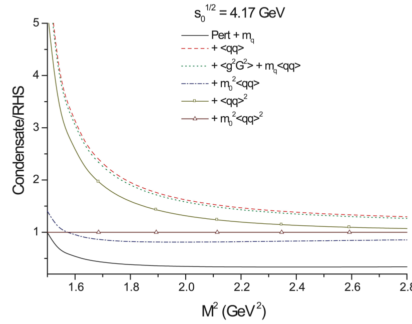

Fig. 1. (color online). The $j_\mu^{(q-di)}$ OPE convergence in the region $1.6\leqslant M^2\leqslant 2.8$ GeV^2 for $\sqrt{s_0}=4.17$ GeV.

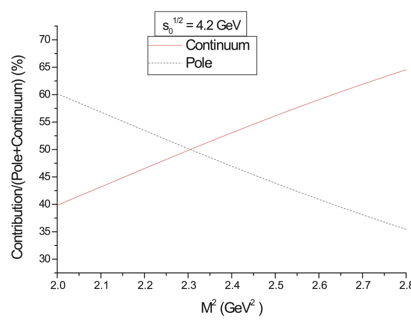

Fig. 2. (color online). The dashed line shows the relative pole contribution (the pole contribution divided by the total, pole plus continuum, contribution) and the solid line shows the relative continuum contribution.

From Fig. 1 one can see that we have a good OPE convergence for $M^2>2.0$ GeV^2 and this fixes the lower limit of the Borel window. We obtain an upper limit for M^2 by imposing that the QCD continuum contribution should be smaller than the pole contribution. The maximum value of M^2 for which this constraint is satisfied depends on the value of s_0. From Fig. 2 we see that for $\sqrt{s_0}=4.2$ GeV we get $M^2\leqslant 2.32$ GeV^2.

The mass obtained in [23] considering the allowed Borel window and the uncertaities in the parameters is

$$M_{\mathrm{X}} = (3.92 \pm 0.13)\ \mathrm{GeV}\,, \tag{13}$$

which is compatible with the experimental value of the mass of the X(3872).

In the case of the current in Eq. (12), the OPE convergence and the pole contribution determine a similar Borel window [24]. The result for the mass obtained in Ref. [24] is

$$M_{\mathrm{X}} = (3.87 \pm 0.07)\ \mathrm{GeV}\,, \tag{14}$$

in an even better agreement with the experimental mass.

Other important point is whether with a tetraquark or molecular structure for the X(3872), it is possible to explain a total width smaller than 2.3 MeV. In Ref. [25] the $\mathrm{XJ}/\psi\mathrm{V}$ coupling constant was evaluated directly from the QCD sum rules by supposing that the X(3872) is described by a tetraquark current. The $\mathrm{XJ}/\psi\omega$ coupling constant was estimated from the sum rule to be [25]:

$$g_{\mathrm{X}\psi\omega} = 13.8 \pm 2.0\,, \tag{15}$$

which gives:

$$\Gamma(\mathrm{X} \rightarrow \mathrm{J}/\psi\ (\mathrm{n}\pi)) = (50 \pm 15)\ \mathrm{MeV}\,. \tag{16}$$

A similar width was obtained in Ref. [26] by using a molecular current like the one in Eq. (12). Therefore, from a QCDSR calculation it is not possible to explain the small width of the X(3872) if it is a pure four-quark state.

To try to solve the problem of the large width in Ref. [26] the X(3872) was treated as a mixture between a $\mathrm{c}\bar{\mathrm{c}}$ current and a molecular current:

$$J^{\mathrm{q}}_{\mu}(x) = \sin(\alpha) j^{(\mathrm{q,mol})}_{\mu}(x) + \cos(\alpha) j^{(\mathrm{q},2)}_{\mu}(x), \tag{17}$$

with $j^{(\mathrm{q,mol})}_{\mu}(x)$ given in Eq. (12) and

$$j^{(\mathrm{q},2)}_{\mu}(x) = \frac{1}{6\sqrt{2}} \langle \bar{q} q \rangle [\bar{c}_{\mathrm{a}}(x) \gamma_{\mu} \gamma_5 c_{\mathrm{a}}(x)]. \tag{18}$$

The necessity of mixing a $\mathrm{c}\bar{\mathrm{c}}$ component with the $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$ molecule was already pointed out in some works [27–30]. In particular, in Ref. [31], a simulation for the production of a bound $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$ state with binding energy as small as 0.25 MeV, obtained a cross section of about two orders of magnitude smaller than the prompt production cross section for the X(3872) observed by the CDF collaboration. The authors of Ref. [31] concluded that S-wave resonant scattering is unlikely to allow the formation of a loosely bound $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$ molecule in high energy hadron collision.

There is no problem in reproducing the experimental mass of the X(3872), using the current in Eq. (17), for a large range of the mixture angle α. However, the value of the $\mathrm{XJ}/\psi\omega$ coupling constant and, therefore, the value of the $\mathrm{X} \rightarrow \mathrm{J}/\psi\ (\mathrm{n}\pi)$ decay width, is strongly dependent on this angle. It was shown in Ref. [26] that for a mixing angle $\alpha = 9^0 \pm 4^0$, it is possible to describe the experimental mass of the X(3872) with a decay width $\Gamma(\mathrm{X} \rightarrow \mathrm{J}/\psi\ (\mathrm{n}\pi)) = (9.3 \pm 6.9)$ MeV, which is compatible with the experimental upper limit. Therefore, in a QCDSR calculation, the X(3872) can be well described basically by a $\mathrm{c}\bar{\mathrm{c}}$ current with a small, but fundamental, admixture of molecular ($\mathrm{D}\bar{\mathrm{D}}^*$) or tetraquark ($[\mathrm{cq}][\bar{\mathrm{c}}\bar{\mathrm{q}}]$) currents.

4 The $\mathrm{Y}(J^{PC} = 1^{--})$ family

Belle and BABAR collaborations have reported the observation of three new states in the $\mathrm{e}^+\mathrm{e}^-$ annihilation through initial state radiation. They are the Y(4260) [5], the Y(4360) [6] and the Y(4660) [8].

The Y(4260) was also observed in the $\mathrm{B}^- \rightarrow \mathrm{Y}(4260)\mathrm{K}^- \rightarrow \mathrm{J}/\psi\pi^+\pi^-\mathrm{K}^-$ decay [32], and CLEO reported two additional decay channels: $\mathrm{J}/\psi\pi^0\pi^0$ and $\mathrm{J}/\psi\mathrm{K}^+\mathrm{K}^-$ [33]. The mass and total width of the Y(4260) is:

$$M_{\mathrm{Y}} = (4252 \pm 7)\ \mathrm{MeV},\ \Gamma_{\mathrm{Y}} = (105 \pm 20)\ \mathrm{MeV}. \tag{19}$$

Repeating the same kind of analysis leading to the observation of the Y(4260) state, in the channel $\mathrm{e}^+\mathrm{e}^- \rightarrow \gamma_{\mathrm{ISR}}\Psi(2S)\pi^+\pi^-$, Belle has identified two distinct peaks [8], Y(4360) and Y(4660), which masses and widths are respectively

$$M = (4361 \pm 13)\ \mathrm{MeV},\ \Gamma = (74 \pm 18)\ \mathrm{MeV}; \tag{20}$$

$$M = (4664 \pm 12)\ \mathrm{MeV},\ \Gamma = (48 \pm 15)\ \mathrm{MeV}. \tag{21}$$

The masses and widths of these three states are not consistent with any of the established 1^{--} charmonium states [34], and they can also be candidates for multiquark states or charmonium hybrids [35].

An interesting interpretation is that the Y(4260) is a charmonium hybrid, since its mass is consistent with old lattice gauge theory and flux tube model predictions. However, more recent lattice simulations [36] and QCD string models calculations [37], predict that the lightest charmonium hybrid has a mass of 4400 MeV. Against the hybrid assignement is the fact that the dominant decay mode for a hybrid would be an open charm meson pair with one S-wave D meson (D, D^*, $\mathrm{D_s}$, $\mathrm{D}^*_{\mathrm{s}}$) and one P-wave D meson (D_1, $\mathrm{D}_{\mathrm{s}1}$) [38].

4.1 QCDSR studies for the Y(4260) and Y(4660) states

We can also use molecular or tetraquark currents, with or without a $s\bar{s}$ pair, to try to describe the $\mathrm{Y}(J^{PC}=1^{--})$ states. The lowest-dimension interpolating operator to describe a $J^{PC}=1^{--}$ tetraquark state with the symmetric spin distribution is given by:

$$j^{\mathrm{q}}_{\mu} = \frac{\epsilon_{\mathrm{abc}}\epsilon_{\mathrm{dec}}}{\sqrt{2}}\big[(q_{\mathrm{a}}^{\mathrm{T}}C\gamma_5 c_{\mathrm{b}})(\bar{q}_{\mathrm{d}}\gamma_{\mu}\gamma_5 C\bar{c}_{\mathrm{e}}^{\mathrm{T}})+ (q_{\mathrm{a}}^{\mathrm{T}}C\gamma_5\gamma_{\mu} c_{\mathrm{b}})(\bar{q}_{\mathrm{d}}\gamma_5 C\bar{c}_{\mathrm{e}}^{\mathrm{T}})\big]. \quad (22)$$

A current with $J^{PC}=1^{--}$ and a symmetrical combination of scalar and vector mesons is given by:

$$j^{\mathrm{q}}_{\mu} = \frac{1}{\sqrt{2}}\big[(\bar{q}_{\mathrm{a}}\gamma_{\mu}c_{\mathrm{a}})(\bar{c}_{\mathrm{b}}q_{\mathrm{b}})+(\bar{c}_{\mathrm{a}}\gamma_{\mu}q_{\mathrm{a}})(\bar{q}_{\mathrm{b}}c_{\mathrm{b}})\big]. \quad (23)$$

In Eqs. (22), (23) the q quark stands for a u, d or s quark. In Ref. [39] a QCD sum rule calculation using these currents was considered. The obtained mass for the $\mathrm{D_0\bar{D}^*}$ current was:

$$m_{\mathrm{D_0\bar{D}^*}} = (4.27\pm0.10)\ \mathrm{GeV}, \quad (24)$$

in good agreement with the Y(4260) mass. For the $\mathrm{D_{s0}\bar{D}_s^*}$ current they obtained:

$$m_{\mathrm{D_{s0}\bar{D}_s^*}} = (4.42\pm0.10)\ \mathrm{GeV}. \quad (25)$$

In the case of the diquark-antidiquark current, the obtained masses were [39]:

$$m_{\mathrm{Y_u}} = (4.49\pm0.11)\ \mathrm{GeV}, \quad (26)$$

and

$$m_{\mathrm{Y_s}} = (4.65\pm0.10)\ \mathrm{GeV}, \quad (27)$$

in good agreement with the Y(4660) mass.

The authors of Ref. [39] concluded that it is possible to interpret the Y(4660) meson as a $[\mathrm{cs}][\overline{\mathrm{cs}}]$ diquark-antidiquark state, and the Y(4260) meson as a molecular $\mathrm{D_0\bar{D}^*}$ state.

5 $\mathrm{Z^+}$(4430)

The $\mathrm{Z^+}$(4430) was observed by Belle collaboration in the decay channel $\mathrm{B^+\to K\psi'\pi^+}$ [7]. The measured mass and width of this state are:

$$M=(4433\pm4\pm2)\ \mathrm{MeV},\ \ \Gamma=(45^{+18+30}_{-13-13})\ \mathrm{MeV}. \quad (28)$$

Using the same data sample as in Ref. [7], Belle also performed a full Dalitz plot analysis [40] and has confirmed the observation of the $\mathrm{Z^+}$(4430) signal with a 6.4σ peak significance.

Babar collaboration [41] also searched the $\mathrm{Z^-}$(4430) signature in four decay modes: $\mathrm{B\to\psi\pi^-K}$, where $\psi=\mathrm{J}/\psi$ or ψ' and $\mathrm{K}=\mathrm{K^0_S}$ or $\mathrm{K^+}$. They concluded that is no significant evidence for a signal peak in any of these processes.

There are no reports of a $\mathrm{Z^+}$ signal in the $\mathrm{J}/\psi\pi^+$ decay channel. Since the minimal quark content of this state is $\mathrm{c\bar{c}u\bar{d}}$, this state is a prime candidate for a multiquark meson.

There are many theoretical interpretations for the $\mathrm{Z^+}$(4430) structure like S-wave threshold effect, $\mathrm{D^*D_1}$ molecular state, tetraquark state or a cusp in the $\mathrm{D^*D_1}$ channel [9]. Considering the $\mathrm{Z^+}$(4430) as a loosely bound S-wave $\mathrm{D^*D_1}$ molecular state, the allowed angular momentum and parity are $J^P=0^-,\ 1^-,\ 2^-$, although the 2^- assignment is probably suppressed in the $\mathrm{B^+\to Z^+K}$ decay by the small phase space. Among the remaining possible 0^- and 1^- states, the former will be more stable as the later can also decay to $\mathrm{DD_1}$ in S-wave. Moreover, one expects a bigger mass for the $J^P=1^-$ state as compared to a $J^P=0^-$ state.

5.1 QCDSR for $\mathrm{Z^+}$(4430)

One can also use tetraquak or molecular currents to study the $\mathrm{Z^+}$(4430) structure. A $\mathrm{D^*D_1}$ molecular current with $J^P=0^-$, considered in Ref. [42], is given by:

$$j=\frac{1}{\sqrt{2}}\left[(\bar{d}_{\mathrm{a}}\gamma_{\mu}c_{\mathrm{a}})(\bar{c}_{\mathrm{b}}\gamma^{\mu}\gamma_5 u_{\mathrm{b}})+(\bar{d}_{\mathrm{a}}\gamma_{\mu}\gamma_5 c_{\mathrm{a}})(\bar{c}_{\mathrm{b}}\gamma^{\mu}u_{\mathrm{b}})\right]. \quad (29)$$

The mass obtained in a QCDSR calculation using such a current was [42]:

$$m_{\mathrm{D^*D_1}} = (4.40\pm0.10)\ \mathrm{GeV}, \quad (30)$$

in an excelent agreement with the experimental mass.

To check if the $\mathrm{Z^+}$(4430) could also be described using diquark-antidiquark currents, the following currents were considered in Ref. [43]:

$$j_{0^-} = \frac{\mathrm{i}\epsilon_{\mathrm{abc}}\epsilon_{\mathrm{dec}}}{\sqrt{2}}\big[(u_{\mathrm{a}}^{\mathrm{T}}C\gamma_5 c_{\mathrm{b}})(\bar{d}_{\mathrm{d}}C\bar{c}_{\mathrm{e}}^{\mathrm{T}})- (u_{\mathrm{a}}^{\mathrm{T}}C c_{\mathrm{b}})(\bar{d}_{\mathrm{d}}\gamma_5 C\bar{c}_{\mathrm{e}}^{\mathrm{T}})\big], \quad (31)$$

for a $J^P=0^-$ state, and

$$j^{1^-}_{\mu} = \frac{\epsilon_{\mathrm{abc}}\epsilon_{\mathrm{dec}}}{\sqrt{2}}\big[(u_{\mathrm{a}}^{\mathrm{T}}C\gamma_5 c_{\mathrm{b}})(\bar{d}_{\mathrm{d}}\gamma_{\mu}\gamma_5 C\bar{c}_{\mathrm{e}}^{\mathrm{T}})+ (u_{\mathrm{a}}^{\mathrm{T}}C\gamma_5\gamma_{\mu} c_{\mathrm{b}})(\bar{d}_{\mathrm{d}}\gamma_5 C\bar{c}_{\mathrm{e}}^{\mathrm{T}})\big]. \quad (32)$$

for a $J^P=1^-$ state.

The masses obtained with these currents are [43]

$$m_{\mathrm{Z}_{(0^-)}} = (4.52\pm0.09)\ \mathrm{GeV}, \quad (33)$$

which is a little bigger than the experimental value, but still consistent with it, considering the uncertainties, and

$$m_{Z_{(1^-)}} = (4.84 \pm 0.14)\ \text{GeV}, \quad (34)$$

which is much bigger than the experimental value and bigger than the result obtained using the current with $J^P = 0^-$ in Eq. (33).

From these results we conclude that while it is also possible to describe the $Z^+(4430)$ with a diquark-antidiquark current with $J^P = 0^-$, the $J^P = 1^-$ configuration is disfavored.

A confirmation of the existence of the $Z^\pm(4430)$ is critical before a complete picture can be drawn. If confirmed, the only open options for the $Z^+(4430)$ structure are tetraquark or molecule. QCDSR calculations favor a molecular structure with $J^P = 0^-$.

6 Conclusions

We have computed the masses of some X, Y and Z states, recently observed by BABAR and Belle collaborations, using the QCDSR. In some cases a tetraquark configuration was favored, as in the case of Y(4660), and in some other cases a molecular configuration was favored, like the cases of X(3872), Y(4260) and $Z^+(4430)$. We have observed that when using tetraquark and molecular currents with same quantum numbers, QCDSR results for the masses are always smaller for molecular currents. This may be considered as an indication that it is easier to form a multiquark state in a molecular configuration than in a diquark-antidiquark configuration.

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