Molecular states with hidden charm and strange in QCD Sum Rules

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Abstract - This work uses the QCD Sum Rules to study the masses of the $D_s\bar{D}^*_s$ and $D_s^*\bar{D}^*_s$ molecular states with quantum numbers $J^{PC} = 1^{+-}$. Interpolating currents with definite C-parity are employed, and the contributions up to dimension eight in the Operator Product Expansion (OPE) are taken into account. The results indicate that two hidden strange charmonium-like states may exist in the energy ranges of 3.83–4.13 GeV and 4.22–4.54 GeV, respectively. The hidden strange charmonium-like states predicted in this work may be accessible in future experiments, e.g., BESIII, BelleII and SuperB. Possible decay modes, which may be useful in further research, are predicted.

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Introduction. – Recently, the BESIII Collaboration claimed that four charged charmonium-like resonances \cite{1} were observed in the invariance mass spectra of $(D\bar{D}^*)^\pm$, $J/\psi\pi^\pm$, $h_c\pi^\pm$ and $(D^*\bar{D}^*)^\pm$, which were respectively referred to as $Z_c(3885)$, $Z_c(3900)$, $Z_c(4020)$ and $Z_c(4025)$. Among them, the $Z_c(3900)$ has been confirmed by the Belle Collaboration \cite{2} and the CLEO-c experiment \cite{3}. So far it is still early to tell whether $Z_c(3885)$ and $Z_c(3900)$, as well as $Z_c(4020)$ and $Z_c(4025)$, are the same state or not. Moreover, very recently, the $Z_c(4430)$, which was first observed by Belle Collaboration \cite{4}, has been confirmed in the LHCb experiment with about 13.9 $\sigma$ of significance \cite{5}. The charmonium-like resonances are of particular interest as they facilitate not only investigating the dynamics of interaction between light quarks and heavy quarks, but also the testing of the standard model itself. Until now, their inner structures have not been well determined by theory. In the literature possible interpretations include molecular states \cite{6–11}, tetraquark states \cite{12–16}, enhancement structures \cite{17,18}, etc.

In refs. \cite{15,16}, $Z_c(4430)$ was treated as a pure tetraquark state, since there is no open charm meson thresholds close to it. It is tempting to think this state to be a radial excitation of the $Z_c(3900)$, which was analyzed in the framework of QCD Sum Rules \cite{19}. Of the hidden strange charmonium-like states, the CDF Collaboration observed a narrow structure $Y(4140)$ near the $J/\psi\phi$ threshold in the exclusive $B^+ \rightarrow J/\psi\phi K^+$ decay mode produced in the $pp$ collision at $\sqrt{s} = 1.96$ TeV \cite{20,21}. A scalar molecular state constructed by $D^*_s\bar{D}^*_s$ with $J^{PC} = 0^{++}$ was proposed to interpret the $Y(4140)$ \cite{22–24} soon after its observation, and the extracted mass coincided with the experimental data.

Utilizing the QCD Sum Rules, researchers have successfully estimated the mass of $Z_c(3900)$ and $Z_c(4025)$ with $DD^*$ and $D^*\bar{D}^*$ currents, respectively \cite{6,11}. These successes have attracted enormous interest from theorists. It is of great interest to note that these states indicate that a new class of hadrons has been observed, but without the strange flavor until now. Namely, two resonances are expected to exist near the thresholds of $D_s\bar{D}^*_s$ and $D^*_s\bar{D}^*_s$ with the quantum numbers $J^{PC} = 1^{+-}$. In this work, we calculate their mass spectra with QCD Sum Rules, discuss the implications of our results and suggest their possible decay channels in the summary. We hope this work may be helpful to experiment in exploring the hidden strange charmonium-like states.

Primary formulae are presented after the introduction. In the third section, the numerical results and related figures are shown. The last section is a short summary.

Formalism. – This work considers $D_s\bar{D}^*_s$ and $D^*_s\bar{D}^*_s$ as molecular states with $J^{PC} = 1^{+-}$ via QCD Sum
The calculations of the QCD Sum Rules are based on the correlator constructed by two hadronic currents. For an axial vector state, the two-point correlation function is given by

$$\Pi_{\mu\nu}(q) = i \int d^4 x e^{iq\cdot x} \langle 0 | T \{ j_\mu(x), j_\nu^\dagger(0) \} | 0 \rangle,$$  \hspace{1cm} (1)

where \( j_\mu(x) \) is a current with quantum numbers \( J^{PC} = 1^{+-} \).

$$j_\mu(x) = \frac{i}{\sqrt{2}} \left[ \bar{s}_a \gamma_\mu c_a + \bar{c}_a \gamma_\mu s_a \right],$$  \hspace{1cm} (2)

$$j_\mu^D(x) = \frac{i}{\sqrt{2}} \left[ \bar{s}_a \gamma_\mu c_a + \bar{c}_a \gamma_\mu s_a - \bar{s}_a \gamma_\mu s_a \right],$$  \hspace{1cm} (3)

for, respectively, \( D_s D_s^* \) and \( D_s^* D_s^* \). Here \( a, b \) are color indices, and these currents keep closer relations respectively with \( Z_3(3900) \) and \( Z_3(4025) \) [6,11].

As \( j_\mu(x) \) is not a conserved current, the two-point correlation function has two independent Lorentz structures [29]:

$$\Pi_{\mu\nu}(q) = - \left( g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) \Pi_0(q^2) + \frac{q_\mu q_\nu}{q^2} \Pi_1(q^2),$$  \hspace{1cm} (4)

where the invariant functions \( \Pi_0(q^2) \) and \( \Pi_1(q^2) \) are respectively related to the spin-0 and spin-1 mesons. In order to study the \( 1^{+-} \) meson state, \( \Pi_1(q^2) \) was utilized.

The fundamental assumption of the QCD Sum Rules is the principle of quark-hadron duality. Accordingly, on the one hand, the correlation function \( \Pi_1(q^2) \) is obtained at the hadron level where the mass and coupling constant of the hadron are introduced. It may be calculated at the quark-gluon level, in which the Operator Product Expansion (OPE) is employed.

On the hadron side, after separating out the ground state contributions from the pole terms, the correlation function \( \Pi_1(q^2) \) is obtained as a dispersion integral over a physical regime,

$$\Pi_1(q^2) = \frac{\lambda_H^2}{M_H^2 - q^2} + \frac{1}{\pi} \int_{s_0}^{\infty} ds \rho_H^0(s) \frac{1}{s - q^2},$$  \hspace{1cm} (5)

in which \( M_H \) is the mass of \( D_s D_s^* \) or \( D_s^* D_s^* \) molecular state with \( J^{PC} = 1^{+-} \), and \( \rho_H^0(s) \) is the spectral density which contains contributions from the higher excited states and continuum states, \( s_0 \) is the threshold of the higher excited states and continuum states, and the coupling constant \( \lambda_H \) is defined by \( [\langle 0 j_\mu(z) \rangle \langle z c_\alpha \rangle] = \lambda_H j_\mu \), where \( Z_{css} \) is the lowest lying \( 1^{+-} D_s^* D_s^* \) or \( D_s^* D_s^* \) molecular state.

On the quark-gluon side, the correlation function \( \Pi_1(q^2) \) can be expressed as a dispersion relation:

$$\Pi_1^{OPE}(q^2) = \int_{(2m_+,2m_+)^2}^{\infty} ds \rho_{OPE}^0(s) \frac{1}{s - q^2} + \Pi_1^{(q^2G^2)}(q^2) + \Pi_1^{(ss)^2}(q^2) + \Pi_1^{(ss)(sG)}(q^2),$$  \hspace{1cm} (6)

in which \( \rho_{OPE}^0(s) = \text{Im}[\Pi_1^{OPE}(s)]/\pi \) and

$$\rho_{OPE}^0(s) = \rho_{pert}^0(s) + \rho_{(ss)}^0(s) + \rho_{(q^2G^2)}^0(s) + \rho_{(sG)}^0(s),$$  \hspace{1cm} (7)

where \( \Pi_1^{(q^2G^2)}(q^2) \), \( \Pi_1^{(ss)^2}(q^2) \) and \( \Pi_1^{(ss)(sG)}(q^2) \) denote those contributions of the correlation function which have no imaginary parts but have nontrivial values under the Borel transform. It should be mentioned that in principle the four-gluon operator, \( (q^2G^2)^2 \), also belongs to the dimension-eight condensate, however, in practice we find it only 1% of the mixed condensate \( \langle \bar{s}s \rangle \langle sG \rangle \) in magnitude, and hence the four-gluon condensate is neglected in the evaluation of this work.

After making a Borel transform of the quark-gluon side,

$$\Pi_1^{OPE}(M_B^2) = \int_{(2m_+,2m_+)^2}^{\infty} ds \rho_{OPE}^0(s)e^{-s/M_B^2} \left[ \Pi_1^{(q^2G^2)}(M_B^2) + \Pi_1^{(ss)^2}(M_B^2) + \Pi_1^{(ss)(sG)}(M_B^2) \right],$$  \hspace{1cm} (8)

To consider the effects induced by the mass of the strange quark, terms which are linear in the strange quark mass \( m_s \) are utilized in the following calculations. For both the \( D_s D_s^* \) and \( D_s^* D_s^* \) molecular states, we put the concrete forms of spectral densities in eq. (8) into the detailed version [30].

Performing the Borel transform on the hadron side (eq. (5)) and matching it to eq. (8), the resultant sum rule for the mass of the hidden strange molecular state \( H \) with \( 1^{+-} \) is

$$M_H(s_0, M_B^2) = \sqrt{\frac{-R_1(s_0, M_B^2)}{R_0(s_0, M_B^2)}},$$  \hspace{1cm} (9)

where \( H \) represents the \( D_s D_s^* \) or \( D_s^* D_s^* \) molecular state and

$$R_0(s_0, M_B^2) = \int_{(2m_+,2m_+)^2}^{s_0} ds \rho_{OPE}^0(s)e^{-s/M_B^2} \left[ \Pi_1^{(q^2G^2)}(M_B^2) + \Pi_1^{(ss)^2}(M_B^2) + \Pi_1^{(ss)(sG)}(M_B^2) \right],$$  \hspace{1cm} (10)

$$R_1(s_0, M_B^2) = \frac{\partial}{\partial M_B^2} R_0(s_0, M_B^2).$$  \hspace{1cm} (11)

**Numerical results.** – In the numerical calculation, the values of the condensates and the quark masses are used as [29,31,32]: \( m_s = (0.13 \pm 0.03) \text{GeV} \), \( m_c(m_c) = (1.23 \pm 0.05) \text{GeV} \), \( m_b(m_b) = (4.24 \pm 0.06) \text{GeV} \), \( \langle qq \rangle = -(0.23 \pm 0.03) \text{GeV}^3 \), \( \langle ss \rangle = (0.8 \pm 0.2) \text{GeV} \), \( \langle q^2 G^2 \rangle = 0.88 \text{GeV}^4 \), \( \langle sG \rangle = m_s^2 \text{GeV} \), \( \langle q^2 G^3 \rangle = 0.045 \text{GeV}^5 \), and \( m_0^2 = 0.8 \text{GeV}^2 \), Here, the strange quark mass is the current quark mass in a mass-independent subtraaction scheme such as \( \overline{\text{MS}} \) at the scale \( \mu = m_s \), whereas the charm and bottom quark masses are the running masses in the \( \overline{\text{MS}} \) scheme. To provide greater clarity
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of choosing these parameters, the primary sources for determining these parameters can be found in refs. [33–35].

To determinate the Borel parameter $M_B^2$ and the threshold parameter $s_0$, we used the following limit constraints, which is the standard procedure for QCD Sum Rules analysis. The sum rule parameter $\tau = 1/M_B^2$ is utilized in our analysis. In the QCD Sum Rules, for choosing the threshold $s_0$ and the parameter $\tau$, there are two criteria [25,26,28]. First, the convergence of the OPE is retained. Therefore, in order to determine their convergence, one needs to compare the relative contributions of each term to the total contributions of the OPE side. The second criterion to constrain the $\tau$ is that the pole contribution (PC), defined as the pole contribution divided by the total contribution (pole plus continuum), is larger than the continuum contribution. In order to safely eliminate the contributions of the higher excited and continuum states, the PC is generally greater than 50% [28,29].

To find a proper value for $\sqrt{s_0}$, we carry out a similar analysis as in ref. [36]. Since the continuum threshold is connected to the mass of the studied state by the relation $\sqrt{s_0} \sim (M_H + \delta)$ GeV, where $\delta$ is about 0.6 GeV, various $\sqrt{s_0}$ satisfying this constraint are taken into account. Among these values, one needs then to find out the proper one which has an optimal window for Borel parameter $M_B^2$. That is, within this window, the physical quantity, here the molecular mass $M_H$, is independent of the Borel parameter $M_B^2$ as much as possible. Through the above procedure one obtains the central value of $\sqrt{s_0}$. However, in practice, in the QCD Sum Rules calculation, it is normally acceptable to vary the $\sqrt{s_0}$ by 0.1 GeV [36], which gives the lower and upper bounds and hence the uncertainties of $\sqrt{s_0}$.

The OPE convergences are illustrated in fig. 1 respectively for $D_s D_s^*$ and $D_s^* D_s^*$. Complying with the first criterion, the upper limit constraints of $\tau$ are $\leq 0.55$ GeV$^{-2}$ and $\tau \leq 0.40$ GeV$^{-2}$ with $\sqrt{s_0} = 4.6$ GeV and $\sqrt{s_0} = 4.9$ GeV.

The result of the PC is shown in fig. 2, which indicates the lower limit constraint of $\tau$. Noting that the lower limit constraint of $\tau$ depends on the threshold value $s_0$, for different $s_0$, there are different lower limits of $\tau$. To determine the value of $s_0$, an analysis similar to ref. [29] was carried out.
Table 1: The lower and upper limit constraints of the Borel parameter \( \tau \) for the \( D_s \bar{D}_s^* \) and \( D_s^* \bar{D}_s^* \) molecular states with different values of \( \sqrt{s_0} \).

| \( D_s \bar{D}_s^* \) | \( \sqrt{s_0} \) (GeV) | \( \tau_{\text{min}} \) (GeV\(^{-2}\)) | \( \tau_{\text{max}} \) (GeV\(^{-2}\)) | \( D_s^* \bar{D}_s^* \) | \( \sqrt{s_0} \) (GeV) | \( \tau_{\text{min}} \) (GeV\(^{-2}\)) | \( \tau_{\text{max}} \) (GeV\(^{-2}\)) |
|----------------|---------------|----------------|----------------|----------------|---------------|----------------|----------------|
| \( 4.7 \) | 0.30 | 0.58 | | \( 5.0 \) | 0.26 | 0.42 |
| \( 4.6 \) | 0.32 | 0.55 | | \( 4.9 \) | 0.28 | 0.40 |
| \( 4.5 \) | 0.33 | 0.53 | | \( 4.8 \) | 0.30 | 0.38 |

Table 2: The effect of a non-vanishing strange quark mass in the molecular states \( D_s \bar{D}_s^* \) and \( D_s^* \bar{D}_s^* \).

| \( \sqrt{s_0} \) (GeV) | \( \tau_{\text{min}} \) (GeV\(^{-2}\)) | \( \tau_{\text{max}} \) (GeV\(^{-2}\)) | mass (GeV) |
|----------------|---------------|----------------|------------|
| \( D_s \bar{D}_s^* \) | 4.6 | 0.32 | 0.55 | \( 3.98 \pm 0.15 \) |
| \( D^* \bar{D}^* \) | 4.4 | 0.34 | 0.51 | \( 3.88 \pm 0.18 \) |
| \( D_s D_s^* \) | 4.9 | 0.28 | 0.40 | \( 4.38 \pm 0.16 \) |
| \( D_s^* \bar{D}_s^* \) | 4.7 | 0.31 | 0.40 | \( 4.29 \pm 0.19 \) |

Eventually, the mass of the \( D_s \bar{D}_s^* \) molecular state was determined to be

\[
M_{H}^{D_s \bar{D}_s^*} = (3.98 \pm 0.15) \text{ GeV},
\]  

where the mass with the optimal stability was extracted with errors stemming from the uncertainties of the quark mass, the condensates, the Borel parameter and the threshold parameter \( \sqrt{s_0} \).

The central value for the mass of the \( D_s \bar{D}_s^* \) molecular state is below that of the meson-meson threshold \( E_{th}[D_s \bar{D}_s^*] \approx 4.08 \text{ GeV} \) by 100 MeV, where the notation \( E_{th}[M_1 M_2] \) represents the corresponding energy of the sum of the masses of the \( M_1 \) and \( M_2 \) mesons. Therefore, the \( D_s \bar{D}_s^*(1^{++}) \) molecular state forms a bound state, which predicts a hidden strange charmonium-like state around 3.98 GeV.

For the \( D_s^* \bar{D}_s^* \) molecular state:

\[
M_{H}^{D_s^* \bar{D}_s^*} = (4.38 \pm 0.16) \text{ GeV}.
\]  

The central value for the mass of the \( D_s^* \bar{D}_s^* \) molecular state is above that of the meson-meson threshold \( E_{th}[D_s^* \bar{D}_s^*] \approx 4.22 \text{ GeV} \) by 160 MeV. Therefore, the \( D_s^* \bar{D}_s^*(1^{++}) \) molecular state forms a resonance, which predicts another hidden strange charmonium-like state around 4.38 GeV.

It is important to compare our results with those obtained in refs. [6,11]. We show these comparisons in table 2. The strange quark effect is not huge, and since we take the similar constraints as in ref. [6], our result on \( D^* \bar{D}^* \) agrees with ref. [6] in the massless limit for strange quark. But in the \( D_s^* \bar{D}_s^* \) case, even in the massless limit our result is 0.25 GeV higher than that in ref. [11] on \( D^* \bar{D}^* \). This is due to the different constraint criteria between this work and [11].
Reference [33] systematically evaluated the masses of the tetraquark systems with various quantum numbers and hidden charm. The results for the hidden-charm and strange tetraquark state with \( J^{PC} = 1^{++} \) are in the region of 3.92–4.34 GeV. Comparing to our results, the masses of the molecular states in our calculation lie in 3.83–4.54 GeV, which covers the tetraquark mass region. Since considerable errors exist, so far we think it is hard to distinguish the underlying quark configurations of the tetraquark states and molecular states.

**Summary.** – This work used the QCD Sum Rules to study the masses of the \( D_s \bar{D}_s^* \) and \( D_s^* \bar{D}_s^* \) molecular states with quantum numbers \( J^{PC} = 1^{++} \). In our calculations, interpolating currents with definite charge parity were employed, and the contributions up to dimension eight in the Operator Product Expansion (OPE) were taken into account. The numerical results were respectively (3.98 ± 0.15) GeV and (4.38 ± 0.16) GeV for the \( D_s \bar{D}_s^* \) and \( D_s^* \bar{D}_s^* \) molecular states.

The central value of the \( D_s \bar{D}_s^* \) molecular state was below the corresponding meson-meson threshold \( E_{th}[D_s \bar{D}_s^*] \approx 4.08 \) GeV of about 100 MeV, which means that such molecular state would be tightly bound. The reason for the relative large binding energy is that the current in eq. (2) is local. Hence they do not represent an object with two mesons separated in space, but rather a compact one with two singlet quark-antiquark pairs. The central value of the \( D_s^* \bar{D}_s^* \) molecular state was above that of its corresponding meson-meson threshold \( E_{th}[D_s^* \bar{D}_s^*] \approx 4.22 \) GeV. Therefore, the \( D_s^* \bar{D}_s^* \) molecular state with \( 1^{++} \) may form a resonance.

In conclusion, considering the uncertainties, our results indicated that two hidden strange charmonium-like states, which may be probed in future experiments, may exist in the energy ranges of 3.83–4.13 GeV and 4.22–4.54 GeV.

To ascertain the hidden strange charmonium-like states through their decays, the following decay modes may be measured: \( e^+e^- \rightarrow (\eta_c + \omega) + \eta, e^+e^- \rightarrow (J/\psi + \eta) + \eta \) and \( e^+e^- \rightarrow (J/\psi + \rho_0) / \eta \) for the \( D_s \bar{D}_s^* \) molecular state, and \( e^+e^- \rightarrow (\eta_c + \phi) + \eta, e^+e^- \rightarrow (J/\psi + \eta') + \eta, e^+e^- \rightarrow (J/\psi + \eta) / \eta \) for the \( D_s^* \bar{D}_s^* \) molecular state.

We suggest future experiments to search for these hidden strange charmonium-like resonances. The BESIII, Belle and BaBar and the forthcoming BelleII and SuperB will facilitate searching for such hidden strange charmonium-like resonances.

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**REFERENCES**

[1] BESIII Collaboration (Ablimk M. et al.), Phys. Rev. Lett., 112 (2014) 022001 (arXiv:1310.1163 [hep-ex]); BESIII Collaboration (Ablimk M. et al.), Phys. Rev. Lett., 110 (2013) 252001 (arXiv:1303.5919 [hep-ex]); BESIII Collaboration (Ablimk M. et al.), Phys. Rev. Lett., 111 (2013) 242001 (arXiv:1309.1896 [hep-ex]); BESIII Collaboration (Ablimk M. et al.), Phys. Rev. Lett., 112 (2014) 132001 (arXiv:1308.2760 [hep-ex]).

[2] Belle Collaboration (Liu Z. Q. et al.), Phys. Rev. Lett., 110 (2013) 252002 (arXiv:1304.0121 [hep-ex]).

[3] Xiao T., Dobbs S., Tomaradze A. and Sethi K. K., Phys. Lett. B, 727 (2013) 366 (arXiv:1304.3036 [hep-ex]).

[4] Belle Collaboration (Choi S. K. et al.), Phys. Rev. Lett., 100 (2008) 142001 (arXiv:0708.1790 [hep-ex]).

[5] LHCh Collaboration (Aaij R. et al.), arXiv:1404.1903 [hep-ex].

[6] Cui C.-Y., Liu Y.-L., Chen W.-B. and Huang M.-Q., J. Phys. G, 41 (2014) 075003 (arXiv:1304.1850 [hep-ph]).

[7] Zhang J.-R., Phys. Rev. D, 87 (2013) 116004 (arXiv:1304.5748 [hep-ph]).

[8] Dias J. M., Navarra F. S., Nielsen M. and Zanetti C. M., Phys. Rev. D, 88 (2013) 016004 (arXiv:1304.6433 [hep-ph]).

[9] Ke H.-W., Wei Z.-T. and Li X.-Q., arXiv:1307.2414 [hep-ph].

[10] Cui C.-Y., Liu Y.-L. and Huang M.-Q., arXiv:1308.3625 [hep-ph].

[11] Chen W., Steele T. G., Du M.-L. and Zhu S.-L., Eur. Phys. J. C, 74 (2014) 2773 (arXiv:1308.5060 [hep-ph]).

[12] Maiani L., Riquer V., Faccini R., Piccinini F., Piloni A. and Polosa A. D., Phys. Rev. D, 87 (2013) 111102(R) (arXiv:1303.6857 [hep-ph]).

[13] Qiao C.-F. and Tang L., arXiv:1307.6654 [hep-ph].

[14] Qiao C.-F. and Tang L., Eur. Phys. J. C, 74 (2014) 2810 (arXiv:1308.3439 [hep-ph]).

[15] Drenska N. V., Faccini R. and Polosa A. D., Phys. Rev. D, 79 (2009) 077502 (arXiv:0902.2803 [hep-ph]).

[16] Maiani L., Piccinini F., Polosa A. D. and Riquer V., arXiv:1405.1551 [hep-ph].

[17] Chen D.-Y. and Liu X., Phys. Rev. D, 84 (2011) 034032 (arXiv:1106.5290 [hep-ph]).

[18] Chen D.-Y., Liu X. and Matsuki T., Phys. Rev. D, 88 (2013) 036008 (arXiv:1304.5845 [hep-ph]).

[19] Wang Z.-G., arXiv:1405.3581 [hep-ph].

[20] CDF Collaboration (Aaltonen T. et al.), Phys. Rev. Lett., 102 (2009) 242002 (arXiv:0903.2229 [hep-ex]).

[21] CDF Collaboration (Aaltonen T. et al.), arXiv:1101.6058 [hep-ex].

[22] Wang Z.-G., Eur. Phys. J. C, 63 (2009) 115 (arXiv:0903.5200 [hep-ex]).

[23] Albuquerque R. M., Bracco M. E., Nucl. Phys. B, 678 (2009) 186 (arXiv:0903.5540 [hep-ex]).

[24] Zhang J.-R. and Huang M.-Q., J. Phys. G, 37 (2010) 025005 (arXiv:0905.4178 [hep-ph]).

[25] Shifman M. A., Vainshtein A. I. and Zakharov V. I., Nucl. Phys. B, 147 (1979) 385; 448.

[26] Reinders L. J. and Rubinstein H. and Yazaki S., Phys. Rep., 127 (1985) 1.

[27] Narison S., World Scientific Lecture Notes in Physics, Vol. 26 (World Scientific) 1989.
[28] Colangelo P. and Khodjamirian A., in At the frontier of Particle Physics - Handbook of QCD, edited by Shifman M. (World Scientific, Singapore) 2001, arXiv:hep-ph/0010175.

[29] Matheus R. D., Narison S., Nielsen M. and Richard J.-M., Phys. Rev. D, 75 (2007) 014005 (hep-ph/0608297).

[30] Qiao C.-F. and Tang L., arXiv:1309.7596 [hep-ph].

[31] Narison S., Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 17 (2002) 1 (hep-ph/0205006).

[32] Nielsen M., Navarra F. S. and Lee S. H., Phys. Rep., 497 (2010) 41 (arXiv:0911.1958 [hep-ph]).

[33] Chen W. and Zhu S.-L., Phys. Rev. D, 83 (2011) 034010 (arXiv:1010.3397 [hep-ph]).

[34] Eidemuller M. and Jamin M., Phys. Lett. B, 498 (2001) 203 (hep-ph/0010334).

[35] Jamin M., Oller J. A. and Pich A., Eur. Phys. J. C, 24 (2002) 237 (hep-ph/0110194).

[36] Finazzo S. I., Nielsen M. and Liu X., Phys. Lett. B, 701 (2011) 101 (arXiv:1102.2347 [hep-ph]).