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## A QCD sum rule calculation for the $Y(4140)$ narrow structure

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### ABSTRACT

We use the QCD sum rules to evaluate the mass of a possible scalar mesonic state that couples to a molecular  $D_s^* \bar{D}_s^*$  current. We find a mass  $m_{D_s^* \bar{D}_s^*} = (4.14 \pm 0.09)$  GeV, which is in an excellent agreement with the recently observed  $Y(4140)$  charmonium state. We consider the contributions of condensates up to dimension-eight, we work at leading order in  $\alpha_s$  and we keep terms which are linear in the strange quark mass  $m_s$ . We also consider a molecular  $D^* \bar{D}^*$  current and we obtain  $m_{D^* \bar{D}^*} = (4.13 \pm 0.10)$ , around 200 MeV above the mass of the  $Y(3930)$  charmonium state. We conclude that it is possible to describe the  $Y(4140)$  structure as a  $D_s^* \bar{D}_s^*$  molecular state or even as a mixture of  $D_s^* \bar{D}_s^*$  and  $D^* \bar{D}^*$  molecular states.

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There is growing evidence that at least some of the new charmonium states recently discovered in the B-factories are non-conventional  $c\bar{c}$  states. Some possible interpretations for these states are mesonic molecules, tetraquarks, or/and hybrid mesons. Some of these new mesons have their masses very close to the meson–meson threshold like the  $X(3872)$  [1] and the  $Z^+(4430)$  [2]. Therefore, a molecular interpretation for these states seems natural. The most recent acquisition for this list of peculiar states is the narrow structure observed by the CDF Collaboration in the decay  $B^+ \rightarrow Y(4140)K^+ \rightarrow J/\psi\phi K^+$ . The mass and width of this structure is  $M = (4143 \pm 2.9 \pm 1.2)$  MeV,  $\Gamma = (11.7^{+8.3}_{-5.0} \pm 3.7)$  MeV [3]. Since the  $Y(4140)$  decays into two  $I^G(J^{PC}) = 0^-(1^{--})$  vector mesons, it has positive C and G parities.

There are already some theoretical interpretations for this structure. Its interpretation as a conventional  $c\bar{c}$  state is complicated because, as pointed out by the CDF Collaboration [3], it lies well above the threshold for open charm decays and, therefore, a  $c\bar{c}$  state with this mass would decay predominantly into an open charm pair with a large total width. In Ref. [4], the authors interpreted the  $Y(4140)$  as the molecular partner of the charmonium-like state  $Y(3930)$ , which was observed by Belle and BaBar Collaborations near the  $J/\psi\omega$  threshold [5]. They concluded that the  $Y(4140)$  is probably a  $D_s^* \bar{D}_s^*$  molecular state with  $J^{PC} = 0^{++}$  or  $2^{++}$ . In Ref. [6] they have interpreted the  $Y(4140)$  as an exotic hybrid charmonium with  $J^{PC} = 1^{-+}$ .

In this work, we use the QCD sum rules (QCDSR) [7–9], to study the two-point function based on a  $D_s^* \bar{D}_s^*$  current with  $J^{PC} = 0^{++}$ , to see if the new observed resonance structure,  $Y(4140)$ , can be interpreted as such molecular state. In previous calculations, the hidden charm mesons  $X(3872)$ ,  $Z^+(4430)$ ,  $Y(4260)$ ,  $Y(4360)$ ,  $Y(4660)$ ,  $Z_1^+(4050)$  and  $Z_2^+(4250)$  have been studied using the QCDSR approach as tetraquark or molecular states [10–16]. In some cases a very good agreement with the experimental mass was obtained.

The starting point for constructing a QCD sum rule to evaluate the mass of a hadronic state,  $H$ , is the correlator function

$$\Pi(q) = i \int d^4x e^{iq \cdot x} \langle 0 | T [j_H(x) j_H^\dagger(0)] | 0 \rangle, \quad (1)$$

where the current  $j_H^\dagger$  creates the states with the quantum numbers of the hadron  $H$ . A possible current that couples with a  $D_s^* \bar{D}_s^*$  molecular state with  $I^G J^{PC} = 0^+ 0^{++}$  is

$$j = (\bar{s}_a \gamma_\mu c_a) (\bar{c}_b \gamma^\mu s_b), \quad (2)$$

where  $a$  and  $b$  are color indices.

The QCD sum rule is obtained by evaluating the correlation function in Eq. (1) in two ways: in the OPE side, we calculate the correlation function at the quark level in terms of quark and gluon fields. We work at leading order in  $\alpha_s$  in the operators, we consider the contributions from condensates up to dimension eight and we keep terms which are linear in the strange quark mass  $m_s$ . In the phenomenological side, the correlation function is calculated by inserting intermediate states for the  $D_s^* \bar{D}_s^*$  molecular scalar

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state. Parameterizing the coupling of the scalar state  $H = D_s^* \bar{D}_s^*$ , to the current  $j$ , in Eq. (2) in terms of the parameter  $\lambda$

$$\langle 0 | j | H \rangle = \lambda, \quad (3)$$

the phenomenological side of Eq. (1) can be written as

$$\Pi^{\text{phen}}(q^2) = \frac{\lambda^2}{M_H^2 - q^2} + \int_0^\infty ds \frac{\rho^{\text{cont}}(s)}{s - q^2}, \quad (4)$$

where the second term in the RHS of Eq. (4) denotes higher scalar resonance contributions.

It is important to notice that there is no one to one correspondence between the current and the state, since the current in Eq. (2) can be rewritten in terms of sum an over tetraquark type currents, by the use of the Fierz transformation. However, the parameter  $\lambda$ , appearing in Eq. (3), gives a measure of the strength of the coupling between the current and the state.

The correlation function in the OPE side can be written as a dispersion relation:

$$\Pi^{\text{OPE}}(q^2) = \int_{4m_c^2}^\infty ds \frac{\rho^{\text{OPE}}(s)}{s - q^2}, \quad (5)$$

where  $\rho^{\text{OPE}}(s)$  is given by the imaginary part of the correlation function:  $\pi \rho^{\text{OPE}}(s) = \text{Im}[\Pi^{\text{OPE}}(s)]$ .

As usual in the QCD sum rules method, it is assumed that the continuum contribution to the spectral density,  $\rho^{\text{cont}}(s)$  in Eq. (4), vanishes bellow a certain continuum threshold  $s_0$ . Above this threshold, it is given by the result obtained with the OPE. Therefore, one uses the ansatz [17]

$$\rho^{\text{cont}}(s) = \rho^{\text{OPE}}(s) \Theta(s - s_0). \quad (6)$$

To improve the matching between the two sides of the sum rule, we perform a Borel transform. After transferring the continuum contribution to the OPE side, the sum rules for the scalar meson, described by a scalar  $D_s^* D_s^*$  molecular current, up to dimension-eight condensates, using factorization hypothesis, can be written as:

$$\lambda^2 e^{-m_{D_s^* D_s^*}^2/M^2} = \int_{4m_c^2}^{s_0} ds e^{-s/M^2} \rho^{\text{OPE}}(s), \quad (7)$$

where

$$\rho^{\text{OPE}}(s) = \rho^{\text{pert}}(s) + \rho^{\langle \bar{s}s \rangle}(s) + \rho^{\langle G^2 \rangle}(s) + \rho^{\text{mix}}(s) + \rho^{\langle \bar{s}s \rangle^2}(s) + \rho^{\text{mix}(\langle \bar{s}s \rangle)}(s), \quad (8)$$

with

$$\begin{aligned} \rho^{\text{pert}}(s) &= \frac{3}{2^9 \pi^6} \int_{\alpha_{\min}}^{\alpha_{\max}} \frac{d\alpha}{\alpha^3} \int_{\beta_{\min}}^{1-\alpha} \frac{d\beta}{\beta^2} (1 - \alpha - \beta) [(\alpha + \beta)m_c^2 - \alpha\beta s]^3 \\ &\quad \times \left( \left[ \frac{(\alpha + \beta)m_c^2 - \alpha\beta s}{\beta} \right] - 4m_c m_s \right), \\ \rho^{\langle \bar{s}s \rangle}(s) &= \frac{3 \langle \bar{s}s \rangle}{2^5 \pi^4} \int_{\alpha_{\min}}^{\alpha_{\max}} \frac{d\alpha}{\alpha} \left\{ m_s \frac{(m_c^2 - \alpha(1 - \alpha)s)^2}{1 - \alpha} \right. \\ &\quad \left. - m_c \int_{\beta_{\min}}^{1-\alpha} d\beta [(\alpha + \beta)m_c^2 - \alpha\beta s] \right\}, \end{aligned}$$

$$\begin{aligned} &\times \left[ \frac{(\alpha + \beta)m_c^2 - \alpha\beta s}{\alpha\beta} - \frac{4m_s m_c}{\beta} \right] \Bigg\}, \\ \rho^{\langle G^2 \rangle}(s) &= \frac{m_c^2 \langle g^2 G^2 \rangle}{2^8 \pi^6} \int_{\alpha_{\min}}^{\alpha_{\max}} \frac{d\alpha}{\alpha^3} \int_{\beta_{\min}}^{1-\alpha} d\beta (1 - \alpha - \beta) \\ &\quad \times [(\alpha + \beta)m_c^2 - \alpha\beta s], \\ \rho^{\text{mix}}(s) &= -\frac{m_0^2 \langle \bar{s}s \rangle}{2^6 \pi^4} \left\{ 3m_c \int_{\alpha_{\min}}^{\alpha_{\max}} \frac{d\alpha}{\alpha} [m_c^2 - \alpha(1 - \alpha)s] \right. \\ &\quad \left. - m_s (8m_c^2 - s) \sqrt{1 - 4m_c^2/s} \right\}, \\ \rho^{\langle \bar{s}s \rangle^2}(s) &= \frac{m_c \langle \bar{s}s \rangle^2}{8\pi^2} \left\{ \sqrt{1 - 4m_c^2/s} (2m_c - m_s) \right. \\ &\quad \left. - m_s m_c^2 \int_0^1 \frac{d\alpha}{\alpha} \delta\left(s - \frac{m_c^2}{\alpha(1 - \alpha)}\right) \right\}, \end{aligned} \quad (9)$$

where the integration limits are given by  $\alpha_{\min} = (1 - \sqrt{1 - 4m_c^2/s})/2$ ,  $\alpha_{\max} = (1 + \sqrt{1 - 4m_c^2/s})/2$ ,  $\beta_{\min} = \alpha_{\max}^2 / (\alpha_{\max} - m_c^2)$ , and we have used  $\langle \bar{s}g\sigma.Gs \rangle = m_0^2 \langle \bar{s}s \rangle$ . We have neglected the contribution of the dimension-six condensate  $\langle g^3 G^3 \rangle$ , since it is assumed to be suppressed by the loop factor  $1/16\pi^2$ . We also include a part of the dimension-8 condensate contributions, related with the mixed condensate-quark condensate contribution:

$$\begin{aligned} \rho^{\text{mix}(\langle \bar{s}s \rangle)}(s) &= -\frac{m_c m_0^2 \langle \bar{s}s \rangle^2}{16\pi^2} \int_0^1 d\alpha \delta\left(s - \frac{m_c^2}{\alpha(1 - \alpha)}\right) \\ &\quad \times \left[ (2m_c - m_s) \left( 1 + \frac{m_c^2}{\alpha(1 - \alpha)M^2} \right) \right. \\ &\quad \left. - \frac{5}{3} m_s \left( 1 - \alpha + \frac{m_c^2}{\alpha M^2} + \frac{m_c^4}{2\alpha^2(1 - \alpha)M^4} \right) \right]. \end{aligned} \quad (10)$$

It is important to point out that a complete evaluation of the dimension-8 condensate, and higher dimension condensates contributions, require more involved analysis [18], which is beyond the scope of this calculation.

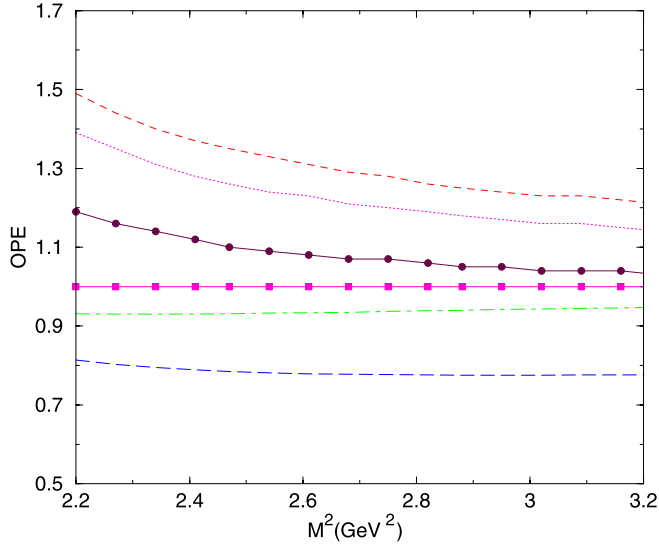
To extract the mass  $m_{D_s^* D_s^*}$  we take the derivative of Eq. (7) with respect to  $1/M^2$ , and divide the result by Eq. (7).

For a consistent comparison with the results obtained for the other molecular states using the QCDSR approach, we have considered here the same values used for the quark masses and condensates as in Refs. [10–16,19]:  $m_c(m_c) = (1.23 \pm 0.05)$  GeV,  $m_s = (0.13 \pm 0.03)$  GeV,  $\langle \bar{q}q \rangle = -(0.23 \pm 0.03)^3$  GeV<sup>3</sup>,  $\langle \bar{s}s \rangle = 0.8 \langle \bar{q}q \rangle$ ,  $\langle \bar{s}g\sigma.Gs \rangle = m_0^2 \langle \bar{s}s \rangle$  with  $m_0^2 = 0.8$  GeV<sup>2</sup>,  $\langle g^2 G^2 \rangle = 0.88$  GeV<sup>4</sup>.

The Borel window is determined by analysing the OPE convergence and the pole contribution. To determine the minimum value of the Borel mass we impose that the contribution of the dimension-8 condensate should be smaller than 20% of the total contribution.

In Fig. 1 we show the contribution of all the terms in the OPE side of the sum rule. From this figure we see that for  $M^2 \geq 2.3$  GeV<sup>2</sup> the contribution of the dimension-8 condensate is less than 20% of the total contribution. Therefore, we fix the lower value of  $M^2$  in the sum rule window as  $M_{\min}^2 = 2.3$  GeV<sup>2</sup>.

The maximum value of the Borel mass is determined by imposing that the pole contribution must be bigger than the continuum



**Fig. 1.** The OPE convergence for the  $D_s^* D_s^*$  molecule in the region  $2.2 \leq M^2 \leq 3.2 \text{ GeV}^2$  for  $\sqrt{s_0} = 4.6 \text{ GeV}$ . We plot the relative contributions starting with the perturbative contribution (long-dashed line), and each other line represents the relative contribution after adding of one extra condensate in the expansion:  $+\langle\bar{s}s\rangle$  (dashed line),  $+\langle g^2 G^2\rangle$  (dotted line),  $+m_0^2\langle\bar{s}s\rangle$  (dot-dashed line),  $+\langle\bar{s}s\rangle^2$  (line with circles),  $+m_0^2\langle\bar{s}s\rangle^2$  (line with squares).

**Table 1**

Upper limits in the Borel window for the  $D_s^* D_s^*$  state obtained from the sum rule for different values of  $\sqrt{s_0}$ .

$\sqrt{s_0}$ (GeV)	$M_{\text{max}}^2$ ( $\text{GeV}^2$ )
4.4	2.49
4.5	2.68
4.6	2.87
4.7	3.06

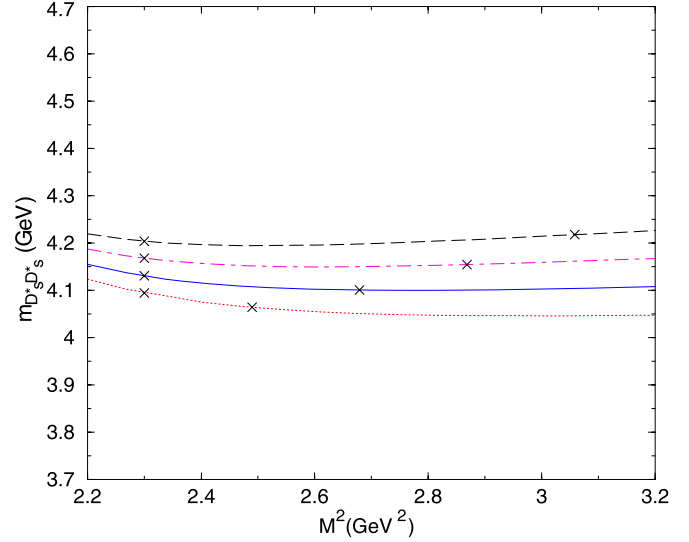
contribution. In Table 1 we show the values of  $M_{\text{max}}^2$ . In our numerical analysis, we will consider the range of  $M^2$  values from  $2.3 \text{ GeV}^2$  until the one allowed by the pole dominance criterion given in Table 1.

The continuum threshold is a parameter of the calculation which, in general, is connected to the mass of the studied state,  $H$ , by the relation  $s_0 \sim (m_H + 0.5 \text{ GeV})^2$ . Therefore, to choose a good range to the value of  $s_0$  we extract the mass from the sum rule, for a given  $s_0$ , and accept such value if the obtained mass is in the range  $0.4 \text{ GeV}$  to  $0.6 \text{ GeV}$  smaller than  $\sqrt{s_0}$ . Using these criteria, we obtain  $s_0$  in the range  $4.5 \leq \sqrt{s_0} \leq 4.7 \text{ GeV}$ . However, because of the complex spectrum of the exotic states, some times lower continuum threshold values are favorable in order to completely eliminate the continuum above the resonance state. Therefore, here we will also include the result for the scalar meson mass for  $\sqrt{s_0} = 4.4 \text{ GeV}$ .

In Fig. 2, we show the scalar meson mass, for different values of  $\sqrt{s_0}$ , in the relevant sum rule window, with the upper and lower validity limits indicated. From this figure we see that the results are very stable as a function of  $M^2$ . We see also that for  $\sqrt{s_0} = 4.4 \text{ GeV}$ , we get a very narrow Borel window, and for  $\sqrt{s_0} = 4.3 \text{ GeV}$  there is no allowed Borel window.

Using the Borel window, for each value of  $s_0$ , to evaluate the mass of the scalar meson and then varying the value of the continuum threshold in the range  $4.4 \leq \sqrt{s_0} \leq 4.7 \text{ GeV}$ , we get  $m_{D_s^* D_s^*} = (4.14 \pm 0.08) \text{ GeV}$ .

Up to now we have kept the values of the quark masses and condensates fixed. To check the dependence of our results with these values we fix  $\sqrt{s_0} = 4.55 \text{ GeV}$  and vary the other parameters



**Fig. 2.** The scalar meson mass, described with a  $D_s^* D_s^*$  molecular current, as a function of the sum rule parameter ( $M^2$ ) for  $\sqrt{s_0} = 4.4 \text{ GeV}$  (dotted line),  $\sqrt{s_0} = 4.5 \text{ GeV}$  (solid line),  $\sqrt{s_0} = 4.6 \text{ GeV}$  (dot-dashed line) and  $\sqrt{s_0} = 4.7 \text{ GeV}$  (dashed line). The crosses indicate the upper and lower limits in the Borel region.

**Table 2**

Values obtained for  $m_{D_s^* D_s^*}$ , in the Borel window  $2.38 \leq M^2 \leq 2.72 \text{ GeV}^2$ , when the parameters vary in the ranges showed.

Parameter	$m_{D_s^* D_s^*}$ (GeV)
$m_c = (1.23 \pm 0.05) \text{ GeV}$	$4.15 \pm 0.08$
$m_s = (0.13 \pm 0.03) \text{ GeV}$	$4.14 \pm 0.02$
$\langle\bar{q}q\rangle = -(0.23 \pm 0.03)^3 \text{ GeV}^3$	$4.14 \pm 0.03$
$m_0^2 = (0.8 \pm 0.1) \text{ GeV}^2$	$4.15 \pm 0.07$
$0.5 \leq K \leq 2$	$4.14 \pm 0.03$

in the ranges:  $m_c = (1.23 \pm 0.05) \text{ GeV}$ ,  $m_s = (0.13 \pm 0.03) \text{ GeV}$ ,  $\langle\bar{q}q\rangle = -(0.23 \pm 0.03)^3 \text{ GeV}^3$ ,  $m_0^2 = (0.8 \pm 0.1) \text{ GeV}^2$ . In our calculation we have assumed the factorization hypothesis. However, it is important to check how a violation of the factorization hypothesis would modify our results. For this reason we multiply  $\langle\bar{s}s\rangle$  in Eqs. (9) and (10) by a factor  $K$  and we vary  $K$  in the range  $0.5 \leq K \leq 2$ . (See Table 2.)

Taking into account the uncertainties given above we finally arrive at

$$m_{D_s^* D_s^*} = (4.14 \pm 0.09) \text{ GeV}, \quad (11)$$

in an excellent agreement with the mass of the narrow structure  $Y(4140)$  observed by CDF.

One can also deduce, from Eq. (7), the parameter  $\lambda$  defined in Eq. (3). We get:

$$\lambda = (4.22 \pm 0.83) \times 10^{-2} \text{ GeV}^5. \quad (12)$$

From the above study it is very easy to get results for the  $D^* \bar{D}^*$  molecular type current with  $J^{PC} = 0^{++}$ . For this we only have to take  $m_s = 0$  and  $\langle\bar{s}s\rangle = \langle\bar{q}q\rangle$  in Eqs. (9), (10). This study was already done in Ref. [15] considering  $4.5 \leq \sqrt{s_0} \leq 4.7 \text{ GeV}$ . Although in the case of the  $D^* \bar{D}^*$  scalar molecular current we get a worse Borel convergence than for the  $D_s^* D_s^*$  scalar molecular current, as can be seen by Fig. 3, there is still a good OPE convergence for  $M^2 \geq 2.5 \text{ GeV}^2$ .

If we allow also for the  $D^* \bar{D}^*$  current values of the continuum threshold in the range  $4.4 \leq \sqrt{s_0} \leq 4.7 \text{ GeV}$  we get  $m_{D^* \bar{D}^*} = (4.13 \pm 0.11) \text{ GeV}$ . Therefore, from a QCD sum rule study, the difference between the masses of the states that couple with scalar  $D_s^* D_s^*$  and  $D^* \bar{D}^*$  currents, is consistent with zero. The mass ob-

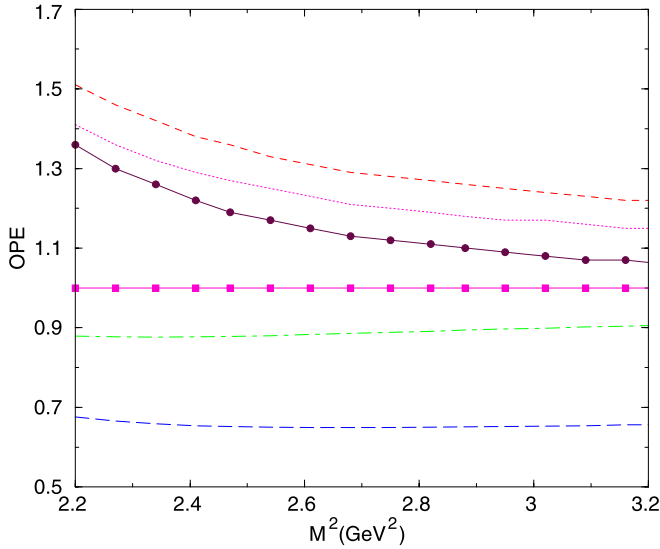


Fig. 3. Same as Fig. 1 for the  $D^*D^*$  current for  $\sqrt{s_0} = 4.6$  GeV.

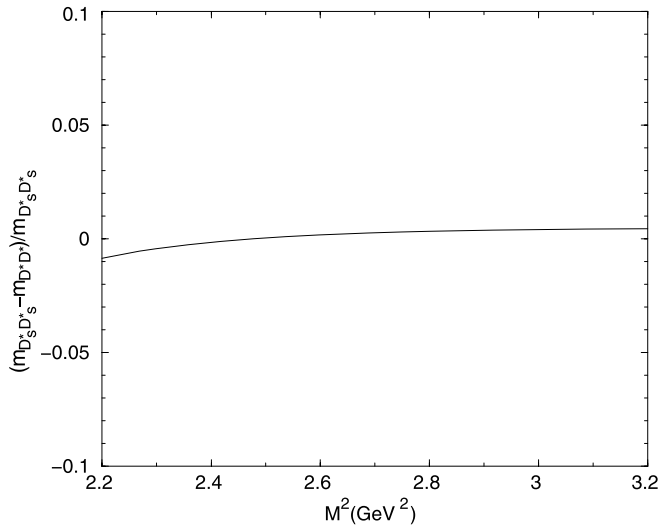


Fig. 4. The relative ratio between the masses of the scalar states  $m_{D_s^*D_s^*}$  and  $m_{D^*D^*}$  for  $\sqrt{s_0} = 4.55$  GeV.

tained with the  $D^*\bar{D}^*$  scalar current is about 100 MeV above the  $D^*D^*$  (4020) threshold. This could be an indication that there is a repulsive interaction between the two  $D^*$  mesons. Strong interactions effects might lead to repulsive interactions that could result in a virtual state above the threshold. Therefore, this structure may or may not indicate a resonance. However, considering the errors, it is not compatible with the observed  $Y(3940)$  charmonium-like state.

In Fig. 4 we show the relative ratio  $(m_{D_s^*D_s^*} - m_{D^*D^*})/m_{D_s^*D_s^*}$  as a function of the Borel mass for  $\sqrt{s_0} = 4.55$  GeV. From this figure we can see that the ratio is very stable as a function of  $M^2$  and the difference between the masses is smaller than 0.5%. Although the ratio is shown for  $\sqrt{s_0} = 4.55$  GeV, the result is indiscernible from the one shown in Fig. 4 for other values of the continuum threshold in the range  $4.4 \leq \sqrt{s_0} \leq 4.7$  GeV.

This result for the mass difference is completely unexpected since, in general, each strange quark adds approximately 100 MeV to the mass of the particle. Therefore, one would naively expect that the mass obtained with the  $D_s^*D_s^*$  current should be around

200 MeV heavier than the mass obtained with the  $D^*D^*$  current. This was, for instance, the result obtained in Ref. [14] for the vector states described with the molecular currents  $D_{s0}\bar{D}_s^*$  and  $D_0\bar{D}^*$ , where the masses obtained were:  $m_{D_{s0}\bar{D}_s^*} = (4.42 \pm 0.10)$  GeV and  $m_{D_0\bar{D}^*} = (4.27 \pm 0.10)$  GeV.

For the value of the parameter  $\lambda$  we get:

$$\lambda_{D^*D^*} = (4.20 \pm 0.96) \times 10^{-2} \text{ GeV}^5. \quad (13)$$

Therefore, comparing the results in Eqs. (12) and (13) we conclude that the currents couple with similar strength to the corresponding states, and that both,  $D_s^*\bar{D}_s^*$  and  $D^*\bar{D}^*$  scalar molecular currents describes scalar mesons with masses compatible with the recently observed  $Y(4140)$  narrow structure. The fact that the  $Y(4140)$  was observed in the decay  $Y(4140) \rightarrow J/\psi\phi$ , could indicate that the  $D_s^*\bar{D}_s^*$  assignment is more compatible with its quark content. However, the  $D^*\bar{D}^*$  assignment cannot be excluded since they have the same quantum numbers. Another interesting interpretation is that the  $Y(4140)$  could be a mixture of these two molecular states.

In conclusion, we have presented a QCDSR analysis of the two-point function based on  $D_s^*\bar{D}_s^*$  and  $D^*\bar{D}^*$  molecular type currents with  $J^{PC} = 0^{++}$ . Our findings indicate that the  $Y(4140)$  narrow structure observed by the CDF Collaboration in the decay  $B^+ \rightarrow Y(4140)K^+ \rightarrow J/\psi\phi K^+$  can be very well described by using a scalar  $D_s^*\bar{D}_s^*$  current or a scalar  $D^*\bar{D}^*$  current. Therefore it is even possible that the  $Y(4140)$  be a mixture of these two molecular states.

Although the authors of Ref. [4] interpreted the  $Y(4140)$  as a  $D_s^*\bar{D}_s^*$  molecular scalar state and the  $Y(3930)$  as a  $D^*\bar{D}^*$  molecular scalar state, we have obtained similar masses for the states that couple with the scalars  $D_s^*\bar{D}_s^*$  and  $D^*\bar{D}^*$  currents. Therefore, from a QCD sum rule point of view, the charmonium-like state  $Y(3930)$ , observed by Belle and BaBar Collaborations, has a mass around 200 MeV smaller than the state that couples with a  $D^*\bar{D}^*$  scalar current and, therefore, cannot be well described by such a current.

While this work has been finalized, a similar calculation was presented in Ref. [20]. However, the author of Ref. [20] arrived to a different conclusion.

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