

New molecular candidates from QCDSR

张建荣

国防科学技术大学

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Zhang & Chen, arXiv:1203.0700 [hep-ph].

Outline

1. Introduction

2. New molecular candidates

3. Summary

1. Introduction

QCD:

- 1) 渐进自由
- 2) 色禁闭：夸克和胶子被囚禁在整体无色的强子里

QCD在高能短程：微扰论

长程，微扰方法失效（强耦合），还不能精确地计算非微扰的贡献

非微扰方法：

Lattice、重整化群、低能有效场论、夸克模型、**QCD求和规则**...

QCD Sum Rules (QCDSR):

Shifman, Vainshtein, Zakharov (SVZ), 1979年

三步骤：

1) 关联函数唯象描述

2) 关联函数**QCD**描述（算符乘积展开）

短程——微扰理论

长程——真空凝聚

3) 匹配两种描述得到强子参量

广泛应用于介子，重子，多夸克态等系统...

Cited 3981

QCDSR方法的优&缺

Molecular states:

M. B. Voloshin and L. B. Okun, JETP Lett. 23, 333 (1976)

A. D. Rujula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 38, 317 (1977)

N. A. Tornqvist, Z. Phys. C 61, 525 (1994)

Y(3930)  $D^* \bar{D}^*$

X. Liu, Z. G. Luo, Y. R. Liu, and S. L. Zhu;
Y. C. Yang and J. L. Ping

Y(4140)  $D_s^* \bar{D}_s^*$

X. Liu and S. L. Zhu; N. Mahajan;
T. Branz *et al.*; G. J. Ding...

Y(4260) 
 $\chi_c \rho^0$
 $\omega \chi_{c1}$

X. Liu, X. Q. Zeng, and X. Q. Li
C. Z. Yuan, P. Wang, and X. H. Mo

Z(4430)  $D^* \bar{D}_1$

C. Meng and K. T. Chao; X. Liu, Y. R. Liu,
W. Z. Deng, and S. L. Zhu

X(4350)  $D_s^* D_s^{0*}$

Zhang&Huang; Y. L. Ma

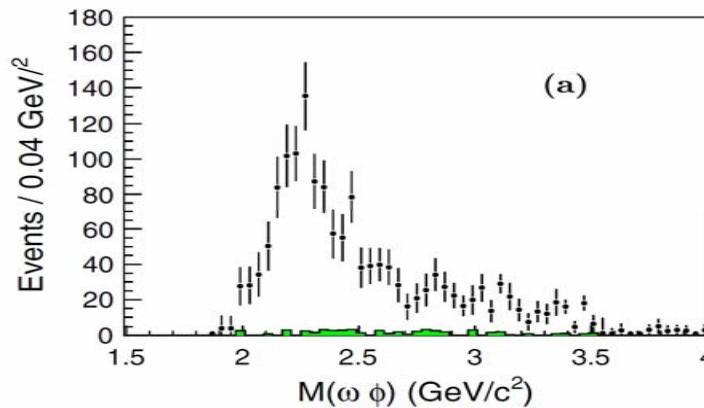
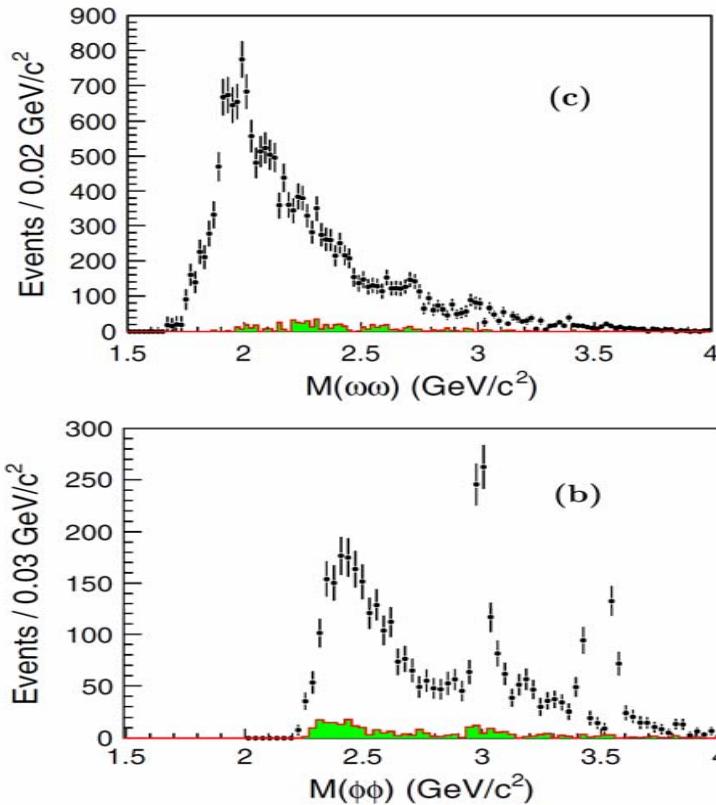
Y(4274)  $D_s D_{s0}(2317)$

X. Liu, Z. G. Luo, and S. L. Zhu

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2. New molecular candidates: X(1910), X(2200), and X(2350)



Z. Q. Liu, C. P. Shen, C. Z. Yuan *et al*,
Belle Collaboration, PRL **108**, 232001
(2012)

刘智青, HFCPV 2012

$\gamma\gamma \rightarrow X \rightarrow \omega\omega, \omega\phi, \text{ and } \phi\phi$

$$M(\omega\omega) \sim 1.91 \text{ GeV}, M(\omega\phi) \sim 2.2 \text{ GeV}, \text{ and } M(\phi\phi) \sim 2.35 \text{ GeV}$$

Here, call X(1910), X(2200), and X(2350)

tetraquark Vs molecular

1. Cross sections lower than predictions of tetraquark model

2. Masses:

H. X. Chen, A. Hosaka, and S. L. Zhu, Phys. Lett. B 650, 369 (2007).

$$J^P = 0^+ \quad q\bar{q}\bar{q}\bar{q} \quad 0.6 \sim 1 \text{ GeV}$$

H. X. Chen, A. Hosaka, and S. L. Zhu, Phys. Rev. D 74, 054001 (2006).

$$J^P = 0^+ \quad u\bar{d}\bar{s}\bar{s} \quad 1.5 \text{ GeV}$$

D. Ebert, R. N. Faustov, and V. O. Galkin, Eur. Phys. J. C 60, 273 (2009).

$$J^P = 0^+ \quad s\bar{s}\bar{s}\bar{s} \quad 2.2 \text{ GeV}$$

Motivation: new molecular states?

Current:

$$j_{\omega\omega} = (\bar{q}_c \gamma^\mu q_c)(\bar{q}_{c'} \gamma_\mu q_{c'})$$

$$j_{\omega\phi} = (\bar{q}_c \gamma^\mu q_c)(\bar{s}_{c'} \gamma_\mu s_{c'})$$

$$j_{\phi\phi} = (\bar{s}_c \gamma^\mu s_c)(\bar{s}_{c'} \gamma_\mu s_{c'})$$

two-point correlator:

$$\Pi(q^2) = i \int d^4x e^{iq \cdot x} \langle 0 | T[j(x) j^+(0)] | 0 \rangle$$

Phenomenological side:

$$\Pi(q^2) = \frac{\lambda_H^2}{M_H^2 - q^2} + \frac{1}{\pi} \int_{s_0}^{\infty} ds \frac{\text{Im}\Pi^{\text{phen}}(s)}{s - q^2} + \text{subtractions}$$

$$\langle 0 | j | H \rangle = \lambda_H$$

OPE side:

$$\Pi(q^2) = \int_{s_{min}}^{\infty} ds \frac{\rho^{\text{OPE}}(s)}{s - q^2} + \Pi^{\text{cond}}(q^2)$$

$$\rho^{\text{OPE}}(s) = \frac{1}{\pi} \text{Im} \Pi^{\text{OPE}}(s)$$

Equating the two sides + quark hadron duality + making a Borel transform

$$\lambda_H^2 e^{-M_H^2/M^2} = \int_{s_{min}}^{s_0} ds \rho^{\text{OPE}} e^{-s/M^2} + \hat{B} \Pi^{\text{cond}}$$

Mass sum rule:

$$M_H^2 = \left\{ \int_{s_{min}}^{s_0} ds \rho^{\text{OPE}} s e^{-\frac{s}{M^2}} + \frac{d(\hat{B} \Pi^{\text{cond}})}{d(-\frac{1}{M^2})} \right\} \Bigg/ \left\{ \int_{s_{min}}^{s_0} ds \rho^{\text{OPE}} e^{-\frac{s}{M^2}} + \hat{B} \Pi^{\text{cond}} \right\}$$

OPE calculations

$$\begin{aligned} S_{ab}(x) = & \frac{i\delta_{ab}}{2\pi^2 x^4} \not{x} - \frac{m_q \delta_{ab}}{4\pi^2 x^2} - \frac{i}{32\pi^2 x^2} t_{ab}^A g G_{\mu\nu}^A (\not{x}\sigma^{\mu\nu} + \sigma^{\mu\nu} \not{x}) - \frac{\delta_{ab}}{12} \langle \bar{q}q \rangle + \frac{i\delta_{ab}}{48} m_q \langle \bar{q}q \rangle \not{x} \\ & - \frac{x^2 \delta_{ab}}{3 \cdot 2^6} \langle g \bar{q} \sigma \cdot G q \rangle + \frac{ix^2 \delta_{ab}}{2^7 \cdot 3^2} m_q \langle g \bar{q} \sigma \cdot G q \rangle \not{x} - \frac{x^4 \delta_{ab}}{2^{10} \cdot 3^3} \langle \bar{q}q \rangle \langle g^2 G^2 \rangle. \end{aligned}$$

with the similar procedure as:

Zhang, Huang: PRD **80**, 056004 (2009);

Zhang, Huang: JHEP **1011**, 057 (2010);

Zhang, Zhong, Huang: PLB **704**, 312 (2011);

Zhang, Huang: PRD **83**, 036005 (2011);

Zhang, Gan, Huang: PRD **85**, 116007 (2012).

spectral density

$$\rho^{\text{pert}}(s) = \frac{1}{5 \cdot 2^{12} \pi^6} s^4, \quad \rho^{\langle \bar{q}q \rangle^2}(s) = \frac{\langle \bar{q}q \rangle^2}{2^3 \pi^2} s, \quad \rho^{\langle \bar{q}q \rangle \langle g\bar{q}\sigma \cdot Gq \rangle}(s) = -\frac{\langle \bar{q}q \rangle \langle g\bar{q}\sigma \cdot Gq \rangle}{2^3 \pi^2},$$

$$\hat{B}\Pi^{\text{cond}} = \frac{\langle g\bar{q}\sigma \cdot Gq \rangle \langle g\bar{q}\sigma \cdot Gq \rangle}{2^6 \pi^2} + \frac{\langle \bar{q}q \rangle^2 \langle g^2 G^2 \rangle}{3^2 \cdot 2^5 \pi^2},$$

for $\omega\omega$ state

$$\rho^{\text{pert}}(s) = \frac{1}{5 \cdot 2^{12} \pi^6} s^4, \quad \rho^{\langle \bar{s}s \rangle^2}(s) = \frac{\langle \bar{s}s \rangle^2}{2^4 \pi^2} s, \quad \rho^{\langle \bar{q}q \rangle^2}(s) = \frac{\langle \bar{q}q \rangle^2}{2^4 \pi^2} s, \quad \rho^{\langle g\bar{s}\sigma \cdot Gs \rangle}(s) = \frac{\langle g\bar{s}\sigma \cdot Gs \rangle}{2^7 \pi^4} m_s s,$$

$$\rho^{\langle \bar{s}s \rangle \langle g^2 G^2 \rangle}(s) = -\frac{\langle \bar{s}s \rangle \langle g^2 G^2 \rangle}{3 \cdot 2^8 \pi^4} m_s, \quad \rho^{\langle \bar{s}s \rangle \langle g\bar{s}\sigma \cdot Gs \rangle}(s) = -\frac{\langle \bar{s}s \rangle \langle g\bar{s}\sigma \cdot Gs \rangle}{2^4 \pi^2}, \quad \rho^{\langle \bar{q}q \rangle \langle g\bar{q}\sigma \cdot Gq \rangle}(s) = -\frac{\langle \bar{q}q \rangle \langle g\bar{q}\sigma \cdot Gq \rangle}{2^4 \pi^2}$$

$$\hat{B}\Pi^{\text{cond}} = -\frac{m_s}{2} \langle \bar{q}q \rangle^2 \langle \bar{s}s \rangle + \frac{\langle g\bar{s}\sigma \cdot Gs \rangle^2}{2^7 \pi^2} + \frac{\langle g\bar{q}\sigma \cdot Gq \rangle^2}{2^7 \pi^2} + \frac{\langle \bar{s}s \rangle^2 \langle g^2 G^2 \rangle}{3^2 \cdot 2^6 \pi^2} + \frac{\langle \bar{q}q \rangle^2 \langle g^2 G^2 \rangle}{3^2 \cdot 2^6 \pi^2},$$

for $\omega\phi$ state

spectral density

$$\rho^{\text{pert}}(s) = \frac{1}{5 \cdot 2^{12} \pi^6} s^4, \quad \rho^{\langle \bar{s}s \rangle^2}(s) = \frac{\langle \bar{s}s \rangle^2}{2^3 \pi^2} s, \quad \rho^{\langle g\bar{s}\sigma \cdot Gs \rangle}(s) = \frac{\langle g\bar{s}\sigma \cdot Gs \rangle}{2^6 \pi^4} m_s s,$$

$$\rho^{\langle \bar{s}s \rangle \langle g^2 G^2 \rangle}(s) = -\frac{\langle \bar{s}s \rangle \langle g^2 G^2 \rangle}{3 \cdot 2^7 \pi^4} m_s, \quad \rho^{\langle \bar{s}s \rangle \langle g\bar{s}\sigma \cdot Gs \rangle}(s) = -\frac{\langle \bar{s}s \rangle \langle g\bar{s}\sigma \cdot Gs \rangle}{2^3 \pi^2},$$

$$\hat{B}\Pi^{\text{cond}} = -m_s \langle \bar{s}s \rangle^3 + \frac{\langle g\bar{s}\sigma \cdot Gs \rangle \langle g\bar{s}\sigma \cdot Gs \rangle}{2^6 \pi^2} + \frac{\langle \bar{s}s \rangle^2 \langle g^2 G^2 \rangle}{3^2 \cdot 2^5 \pi^2},$$

for $\phi\phi$ state

input values

$$m_s = 0.10_{-0.02}^{+0.03} \text{ GeV}$$

$$\langle \bar{q}q \rangle = -(0.23 \pm 0.03)^3 \text{ GeV}^3$$

$$\langle \bar{s}s \rangle = -(0.8 \pm 0.1) \times (0.23 \pm 0.03)^3 \text{ GeV}^3$$

$$\langle g\bar{q}\sigma \cdot Gq \rangle = m_0^2 \langle \bar{q}q \rangle$$

$$\langle g\bar{s}\sigma \cdot Gs \rangle = m_0^2 \langle \bar{s}s \rangle$$

$$m_0^2 = 0.8 \pm 0.1 \text{ GeV}^2$$

$$\langle g^2 G^2 \rangle = 0.88 \text{ GeV}^4$$

1. OPE convergence

2. pole dominance

3. $\sqrt{s_0} \sim M_H + 0.5\text{GeV}$

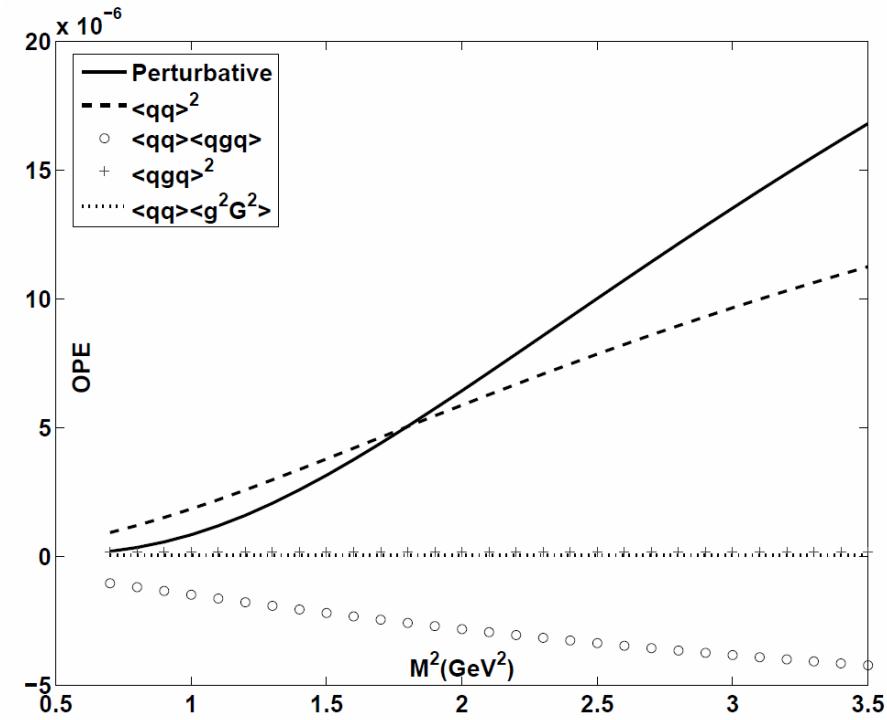
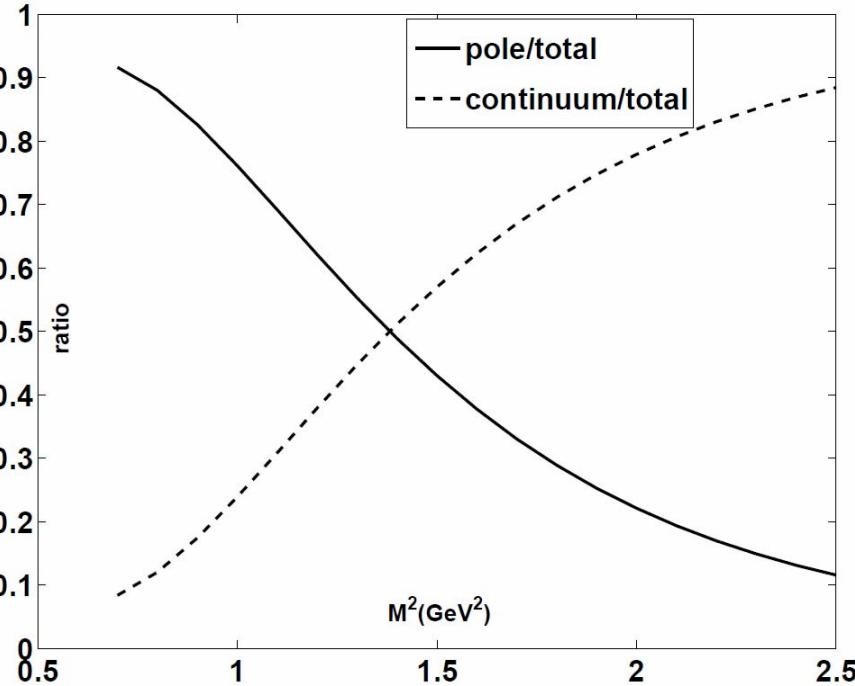


FIG. 1: In the left panel, the solid line shows the relative pole contribution (the pole contribution divided by the total, pole plus continuum contribution) and the dashed line shows the relative continuum contribution from sum rule (6) for $\sqrt{s_0} = 2.4$ GeV for $\omega\omega$ state. The OPE convergence is shown by comparing the perturbative with other condensate contributions from sum rule (6) for $\sqrt{s_0} = 2.4$ GeV for $\omega\omega$ state in the right panel.

1.97 ± 0.17 GeV for $\omega\omega$ state

$M(\omega\omega) \sim 1.91$ GeV

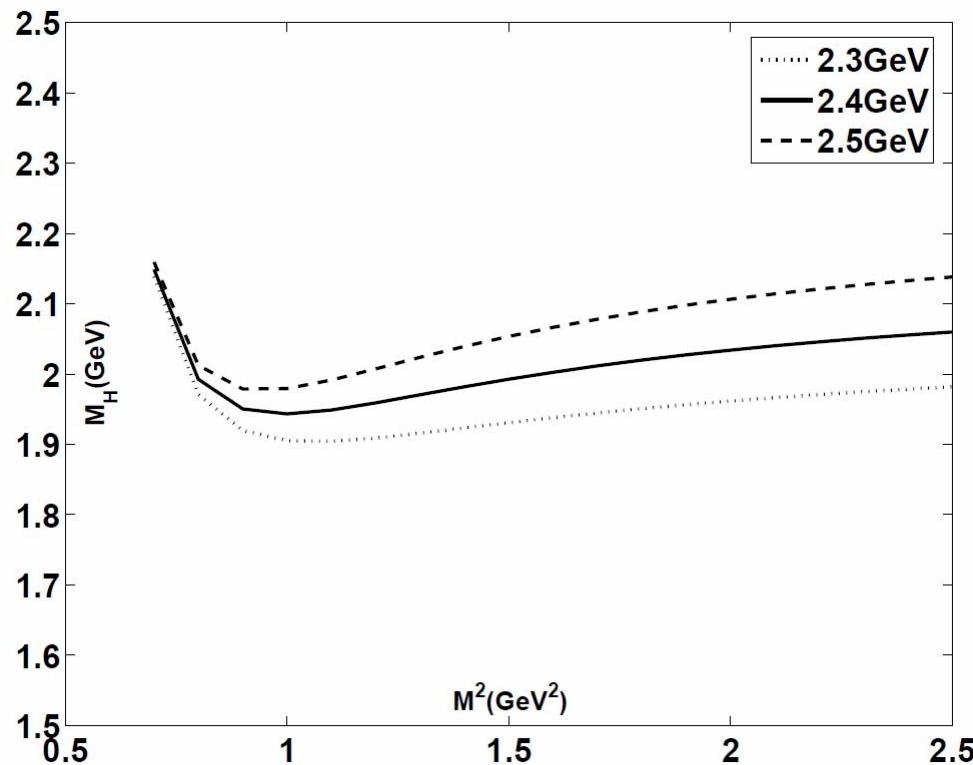


FIG. 2: The mass of $\omega\omega$ state as a function of M^2 from sum rule (7) is shown. The continuum thresholds are taken as $\sqrt{s_0} = 2.3 \sim 2.5$ GeV. For $\sqrt{s_0} = 2.3$ GeV, the range of M^2 is $0.8 \sim 1.2$ GeV^2 ; for $\sqrt{s_0} = 2.4$ GeV, the range of M^2 is $0.8 \sim 1.3$ GeV^2 ; for $\sqrt{s_0} = 2.5$ GeV, the range of M^2 is $0.8 \sim 1.4$ GeV^2 .

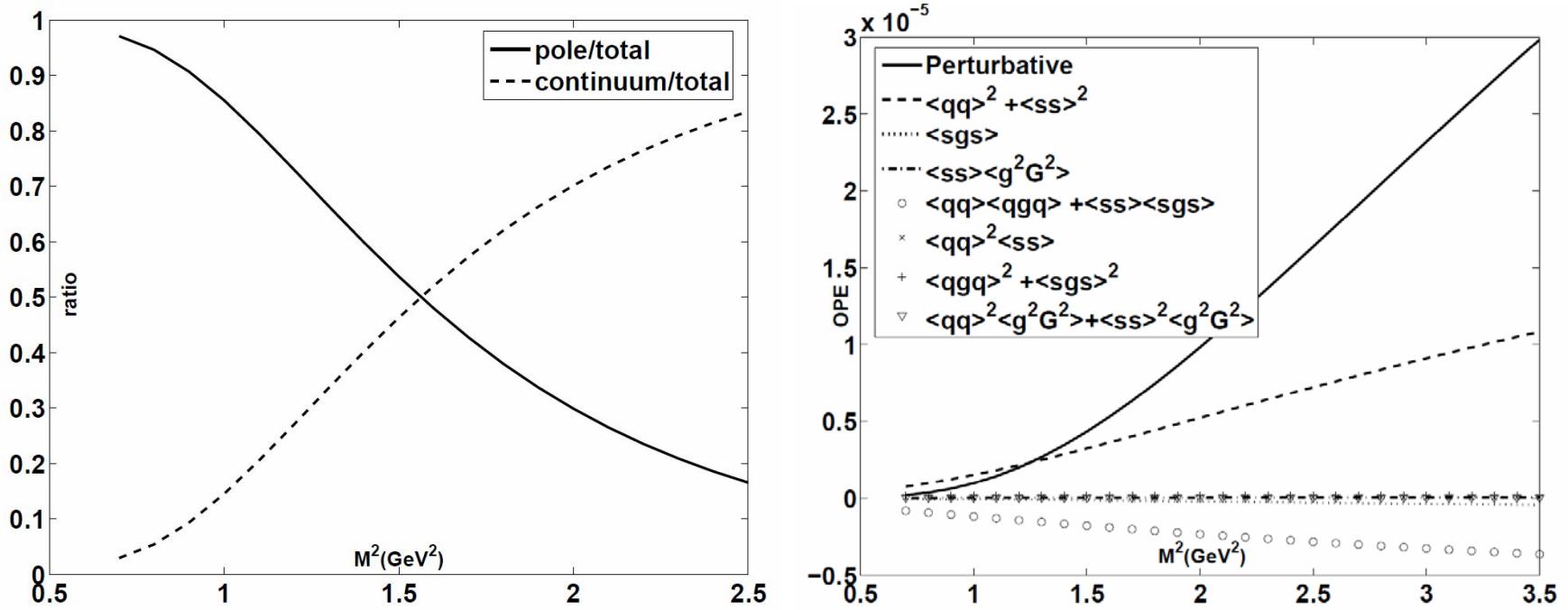


FIG. 3: In the left panel, the solid line shows the relative pole contribution (the pole contribution divided by the total, pole plus continuum contribution) and the dashed line shows the relative continuum contribution from sum rule (6) for $\sqrt{s_0} = 2.6$ GeV for $\omega\phi$ state. The OPE convergence is shown by comparing the perturbative with other condensate contributions from sum rule (6) for $\sqrt{s_0} = 2.6$ GeV for $\omega\phi$ state in the right panel.

2.07 ± 0.21 GeV for $\omega\phi$ state

$M(\omega\phi) \sim 2.2$ GeV

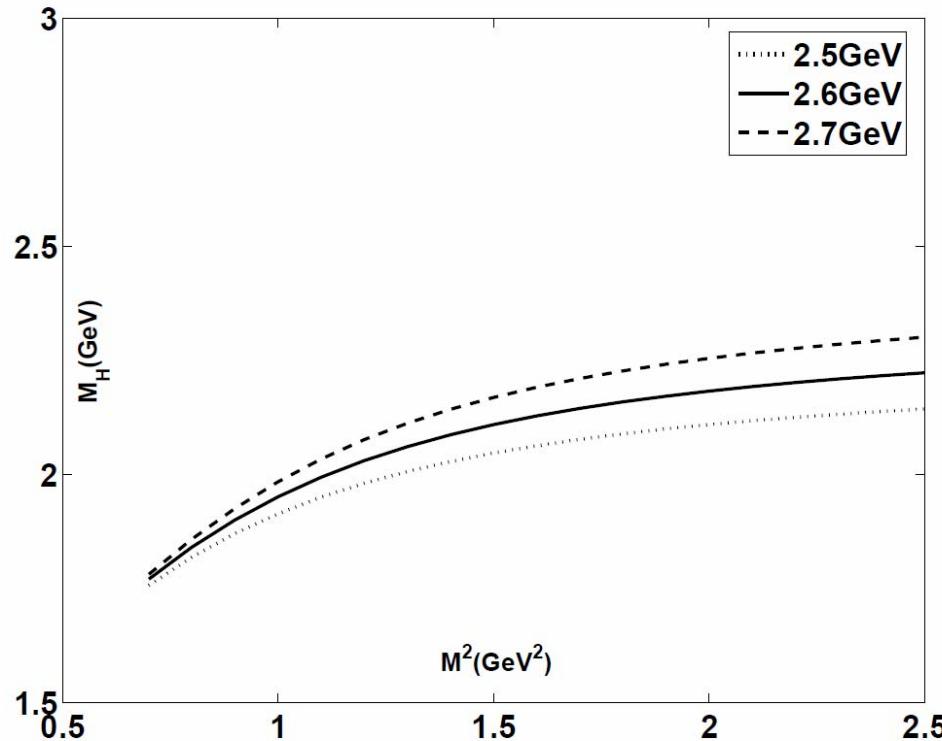


FIG. 4: The mass of $\omega\phi$ state as a function of M^2 from sum rule (7) is shown in the right panel. The continuum thresholds are taken as $\sqrt{s_0} = 2.5 \sim 2.7$ GeV. For $\sqrt{s_0} = 2.5$ GeV, the range of M^2 is $1.1 \sim 1.4$ GeV^2 ; for $\sqrt{s_0} = 2.6$ GeV, the range of M^2 is $1.1 \sim 1.5$ GeV^2 ; for $\sqrt{s_0} = 2.7$ GeV, the range of M^2 is $1.1 \sim 1.6$ GeV^2 .

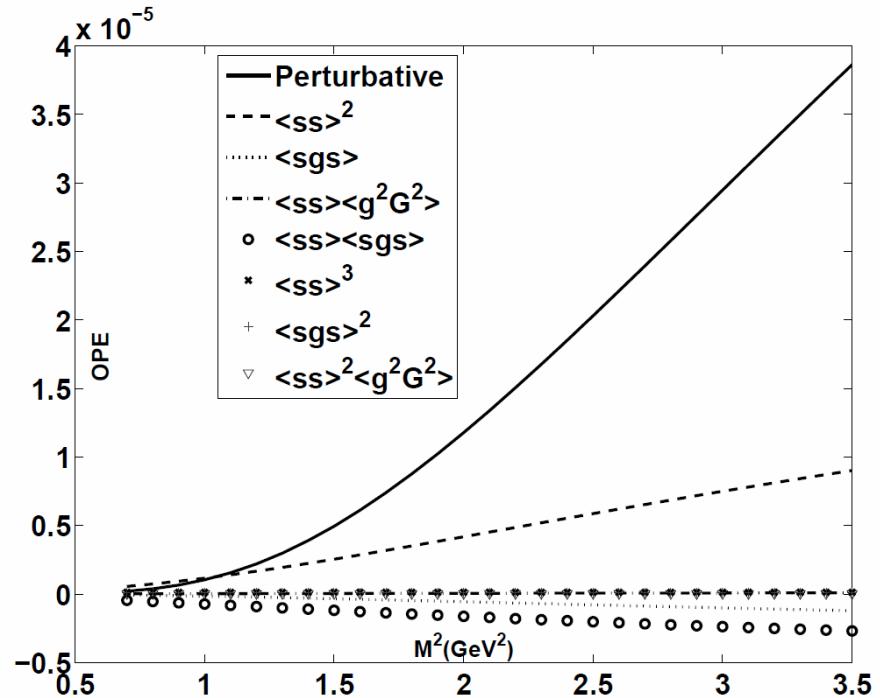
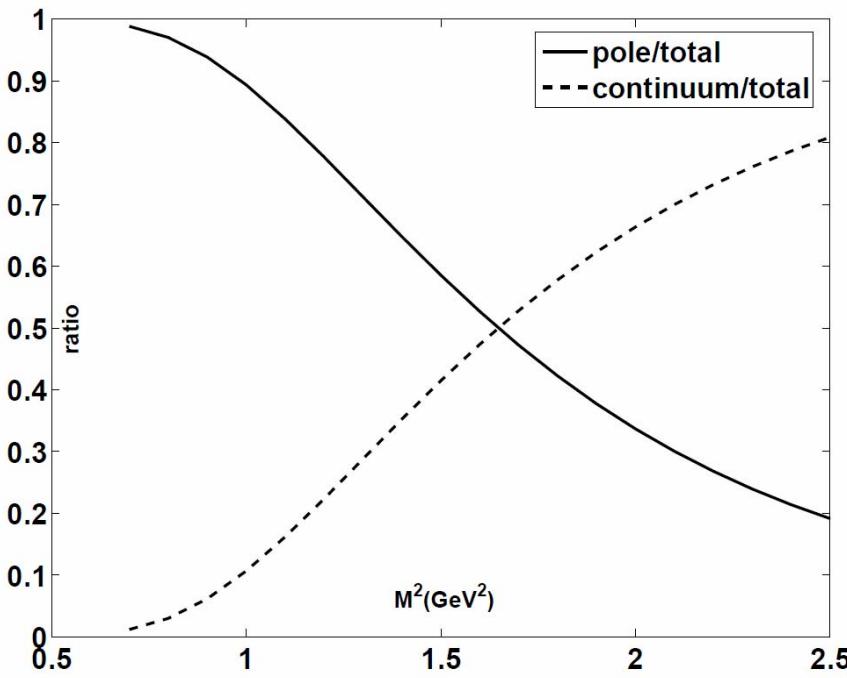


FIG. 5: In the left panel, the solid line shows the relative pole contribution (the pole contribution divided by the total, pole plus continuum contribution) and the dashed line shows the relative continuum contribution from sum rule (6) for $\sqrt{s_0} = 2.7$ GeV for $\phi\phi$ state. The OPE convergence is shown by comparing the perturbative with other condensate contributions from sum rule (6) for $\sqrt{s_0} = 2.7$ GeV for $\phi\phi$ state in the right panel.

2.18 ± 0.29 GeV for $\phi\phi$ state

$M(\phi\phi) \sim 2.35$ GeV

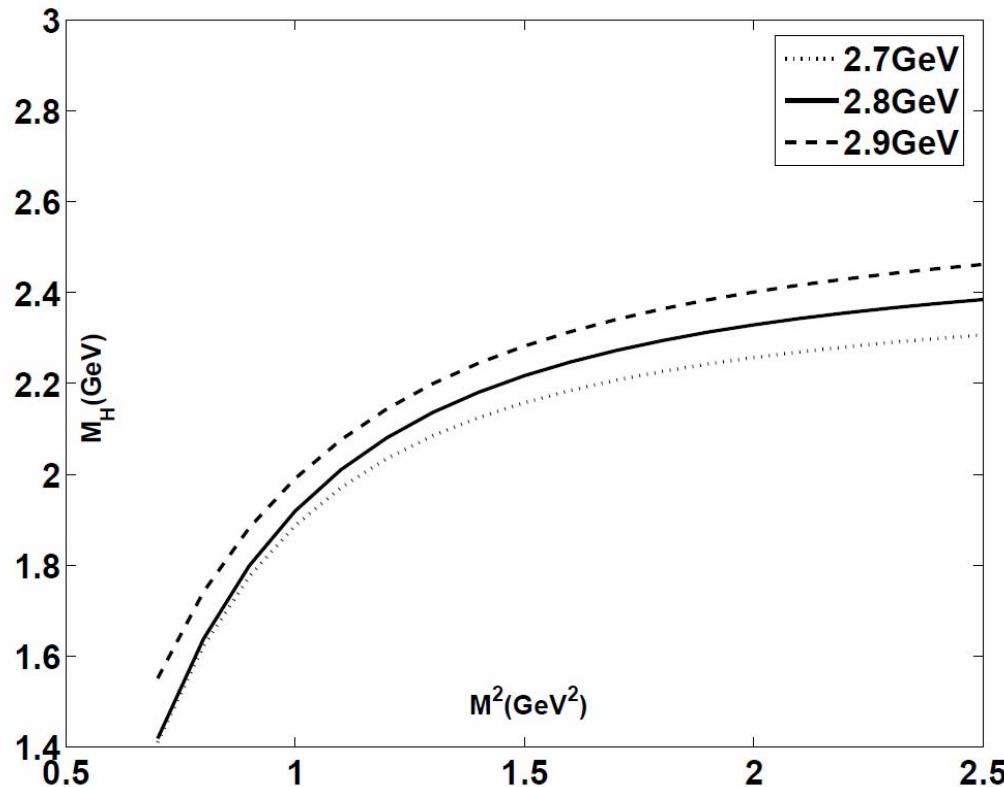


FIG. 6: The mass of $\phi\phi$ state as a function of M^2 from sum rule (7) is shown. The continuum thresholds are taken as $\sqrt{s_0} = 2.7 \sim 2.9$ GeV. For $\sqrt{s_0} = 2.7$ GeV, the range of M^2 is $1.1 \sim 1.6$ GeV 2 ; for $\sqrt{s_0} = 2.8$ GeV, the range of M^2 is $1.1 \sim 1.7$ GeV 2 ; for $\sqrt{s_0} = 2.9$ GeV, the range of M^2 is $1.1 \sim 1.8$ GeV 2 .

3. Summary

- 1) Assuming the newly observed resonant structures $X(1910)$, $X(2200)$, and $X(2350)$ as $\omega\omega$, $\omega\phi$, and $\phi\phi$ molecular states respectively, we compute their mass values in the framework of QCD sum rules. The numerical results are 1.97 ± 0.17 GeV for $\omega\omega$ state, 2.07 ± 0.21 GeV for $\omega\phi$ state, and 2.18 ± 0.29 GeV for $\phi\phi$ state, which coincide with the experimental values of $X(1910)$, $X(2200)$, and $X(2350)$, respectively. This supports the statement that $X(1910)$, $X(2200)$, and $X(2350)$ could be $\omega\omega$, $\omega\phi$, and $\phi\phi$ molecular candidates respectively.
- 2) The differences between our central values and experimental data are probably caused by that we have not considered the spin-2 components, which implies that the theoretical predictions might be improved by including $J = 2$ components for the future.
- 3) One needs to take into account other dynamical analysis to identify the nature structures of these states for further work.

Thanks!