Novel charmonium-like structures in the $J/\psi\phi$ and $J/\psi\omega$ invariant mass spectra

Xiang Liu[1,2] *†
[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China*

Zhi-Gang Luo and Shi-Lin Zhu‡§
Department of Physics and State Key Laboratory of Nuclear Physics and Technology
Peking University, Beijing 100871, China

(Dated: November 5, 2010)

Stimulated by the new evidence of $Y(4274)$ observed in the $J/\psi\phi$ invariant mass spectrum, we first propose the charmonium-like state $Y(4274)$ as the S-wave $D_s\bar{D}_{s0}(2317) + h.c.$ molecular state with $J^P = 0^-$, which is supported well by dynamics study of the system composed of the pseudoscalar and scalar charmed mesons. The S-wave $D\bar{D}_0(2400) + h.c.$ molecular charmonium appears as the molecular partner of $Y(4274)$, which is in accord with the enhancement structure appearing at 4.2 GeV in the $J/\psi\omega$ invariant mass spectrum from B decays. Our study shows that the enhancement structures, *i.e.*, the newly observed $Y(4274)$ and the previously announced $Y(4140)/Y(3930)$ in the $J/\psi\phi$ and $J/\psi\omega$ invariant mass spectra, can be understood well under the uniform framework of the molecular charmonium, which can be tested by future experiments.

PACS numbers: 14.40.Rt, 14.40.Lb, 12.39.Pn

Very recently the CDF Collaboration [1] studied the $J/\psi\phi$ invariant mass spectrum in the $B \to J/\psi\phi K$ channel based on the sample of $p\bar{p}$ collision data with an integrated luminosity of 6 fb^{-1}. Besides confirming the previous $Y(4140)$ state [2], CDF also reported the observation of an explicit enhancement structure with 3.1σ significance in the $J/\psi\phi$ invariant mass spectrum, which is of mass $M = 4274.4^{\pm 8.4}_{-6.7}$(stat) MeV and width $\Gamma = 32.3^{+21.9}_{-15.3}$(stat) MeV [1]. We will refer to this new structure by the name $Y(4274)$ in this letter.

The appearance of $Y(4274)$ in the $J/\psi\phi$ invariant mass spectrum not only makes the charmonium-like family abundant, but also raises our interest in exploring the origin of enhancement structures in the $J/\psi\phi$ invariant mass spectrum and revealing the relation between $Y(4274)$ and $Y(4140)$, which will be helpful to improve our knowledge of the underlying properties of charmonium-like state.

The previous observation of $Y(4140)$ has stimulated great interest among theorists, especially when associating it with $Y(3930)$ reported by the Belle Collaboration [3] and confirmed by the BaBar Collaboration [4]. Both $Y(4140)$ and $Y(3930)$ were observed in the mass spectrum of J/ψ + *light vector meson* in B meson decay

$$B \to K + \left\{ \begin{array}{l} \underline{J/\psi\phi} \Longrightarrow Y(4140) \\ \underline{J/\psi\omega} \Longrightarrow Y(3930) \end{array} \right. .$$

Generally in the weak decays of B meson, the $c\bar{c}$ pair creation mainly results from the color-octet mechanism. Furthermore, a color-octet $q\bar{q}$ pair is easily popped out by a gluon.

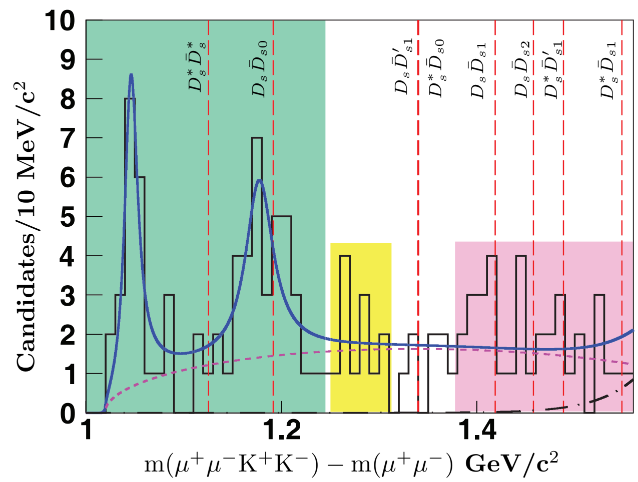

FIG. 1: (Color online.) The mass difference $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ distribution (histogram) for events in the B^+ mass window [1]. Besides $Y(4140)$, one explicit enhancement appears around 4274 MeV. Here, the purple dashed line is the background from the three-body phase space. The blue solid line is the fitting result with resonance parameters of $Y(4140)$ and $Y(4270)$ resonances in Ref. [1]. The vertical red dashed lines denote the thresholds of $D_s^*\bar{D}_s^*$, $D_s\bar{D}_{s0}(2317)$, $D_s\bar{D}'_{s1}(2460)$, $D_s^*\bar{D}_{s0}(2317)$, $D_s\bar{D}_{s1}(2536)$, $D_s\bar{D}_{s2}(2573)$, $D_s^*\bar{D}'_{s1}(2460)$ and $D_s^*\bar{D}_{s1}(2536)$.

Thus, c and $\bar{c}$ capture $\bar{q}$ and q respectively to form a pair of charmed mesons. By this mechanism, a pair of the charm-strange mesons with the low momentum easily interact with each other and even form the molecular charmonium. Additionally, $Y(4140)$ and $Y(3930)$ are close to the thresholds of $D_s^*\bar{D}_s^*$ and $D^*\bar{D}^*$ respectively, and satisfy an almost exact mass relation

$$M_{Y(4140)} - 2M_{D_s^*} \approx M_{Y(3930)} - 2M_{D^*}. \qquad (1)$$

The mass difference between $Y(4140)$ and $Y(3930)$ is approximately equal to that between ϕ and ω mesons: $M_{Y(4140)}$ −

*Corresponding authors.
‡Corresponding authors.
†Electronic address: xiangliu@lzu.edu.cn
§Electronic address: zhusl@pku.edu.cn

$M_{Y(3930)} \sim M_\phi - M_\omega$. The peculiarity of $B \to K(c\bar{c})$ and the similarity between $Y(4140)$ and $Y(3930)$ provoke an uniform molecular charmonium picture to reveal the underlying structure of $Y(4140)$ and $Y(3930)$ [5, 6]. Applying $D_s^*\bar{D}_s^*$ and $D^*\bar{D}^*$ molecular structures to explain $Y(4140)$ and $Y(3930)$ respectively not only solves a long-standing puzzle of the structure of $Y(3930)$, but also opens a window to investigate the hadron dynamics of exotic state beyond the conventional $q\bar{q}$ and qqq states. A series of research work related with $Y(4140)$ were carried out later [5–19].

In Fig. 1, we present the comparison between the experimental data [1] and the thresholds of the charmed-strange meson pairs. $Y(4274)$ is just below the threshold of $D_s\bar{D}_{s0}(2317)$ similar to the situation of $Y(4140)$, which stimulates us to deduce naturally that $Y(4274)$ enhancement results from an S-wave $D_s\bar{D}_{s0}(2317)+h.c.$ molecular system $Y^{s\bar{s}}$ with the flavor wave function

$$|Y^{s\bar{s}}\rangle = \frac{1}{\sqrt{2}}\Big[|D_s^+D_{s0}^-\rangle + |D_s^-D_{s0}^+\rangle\Big]. \quad (2)$$

The C parity of the isoscalar $Y(4274)$ is positive due to the $Y(4274) \to J/\psi\phi$ decay mode observed by CDF. As the cousin of $Y^{s\bar{s}}$, $Y^{u\bar{u}/d\bar{d}}$ is of the flavor wave function

$$|Y^{u\bar{u}/d\bar{d}}\rangle = \frac{1}{2}\Big[|\bar{D}_0^0D^0\rangle + |D_0^0\bar{D}^0\rangle + |D_0^-D^+\rangle + |D_0^+D^-\rangle\Big]. \quad (3)$$

For such S-wave pseudoscalar-scalar systems, their quantum number must be $J^P = 0^-$. Performing dynamical investigations of $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ can answer whether there exist $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ molecular systems, which is one of the main tasks of this letter. What is more important is that understanding the underlying structure of $Y(4274)$ will be helpful for revealing the properties of $Y(4140)$ [5, 6] taking into account the similarities between $Y(4274)$ and $Y(4140)$.

Using the effective Lagrangian in the heavy meson chiral perturbation theory (HMχPT) [20, 21] and the method developed in literature [23], we obtain the effective potentials of $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ states [24]

$$\mathfrak{V}_{eff}^{s\bar{s}}(r) = V_\phi^{Direct}(r) + \frac{2}{3}V_\eta^{Cross}(r), \quad (4)$$

$$\mathfrak{V}_{eff}^{u\bar{u}/d\bar{d}}(r) = \frac{3}{2}V_\rho^{Direct}(r) + \frac{1}{2}V_\omega^{Direct}(r) + V_\sigma^{Direct}(r) + \frac{3}{2}V_\pi^{Cross}(r) + \frac{1}{6}V_\eta^{Cross}(r). \quad (5)$$

Here, the subscript of the sub-potential denotes the exchanged light meson. The general expressions of the sub-potentials corresponding to the pseudoscalar, sigma and vector meson exchanges are

$$V_V^{Direct}(r) = -\frac{\beta\beta'}{2}g_V^2 Y(\Lambda, q_0 = 0, m_V, r), \quad (6)$$

$$V_\sigma^{Direct}(r) = -g_\sigma g'_\sigma Y(\Lambda, q_0 = 0, m_\sigma, r), \quad (7)$$

$$V_P^{Cross}(r) = \frac{h^2 {q'_0}^2}{f_\pi^2} Y(\Lambda, q'_0, m_P, r), \quad (8)$$

where $f_\pi = 132$ MeV and $g_V = m_\rho/f_\pi = 5.8$. g_V, h, $\beta^{(\prime)}$, $g_\sigma^{(\prime)}$ are the parameters in the effective Lagrangian, which describe the interaction of the heavy flavor mesons with the light mesons [21]. q'_0 is taken as $m_{D_{s0}} - m_{D_s}$ and $m_{D_0} - m_D$ for $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$, respectively. And the Y function is

$$Y(\Lambda, \kappa, m, r) = \begin{cases} \text{if } |\kappa| \le m, & -\frac{1}{4\pi r}\left(e^{-\zeta_1 r} - e^{-\zeta_2 r}\right) + \frac{1}{8\pi}\frac{\zeta_2^2-\zeta_1^2}{\zeta_2}e^{-\zeta_2 r} \\ \text{otherwise}, & -\frac{1}{4\pi r}\left(\cos(\zeta'_1 r) - e^{-\zeta_2 r}\right) + \frac{1}{8\pi}\frac{\zeta_2^2+\zeta_1'^2}{\zeta_2}e^{-\zeta_2 r} \end{cases}$$

with $\zeta_1 = \sqrt{m^2-\kappa^2}$, $\zeta'_1 = \sqrt{\kappa^2 - m^2}$ and $\zeta_2 = \sqrt{\Lambda^2-\kappa^2}$. Λ is the cutoff to cure the singularity of the effective potential.

In Fig. 2, one presents the line shapes of the potentials listed in Eqs. (4) and (5). For $Y^{s\bar{s}}$, the exchange potential of the ϕ meson can be ignored compared with that of the η meson. The total effective potential of $Y^{s\bar{s}}$ is dominated by the η exchange potential. For $Y^{u\bar{u}/d\bar{d}}$, the π meson plays an important role especially in the range of $r > 5\,\text{GeV}^{-1}$ since the exchange potentials of ρ, ω, σ and η decay exponentially with r. The behavior of the potential depicted in Fig. 2 indicates that we only need to consider the η meson exchange potential for $Y^{s\bar{s}}$ and the π meson exchange potential for $Y^{u\bar{u}/d\bar{d}}$ when finding the bound state solution by solving Schrödinger equation. Furthermore, whether there exist bound state solutions for $Y^{s\bar{s}}$ and $Y^{u\bar{u}/d\bar{d}}$ systems is closely related to the corresponding strengths of the $D_{s0}(2317)D_s\eta$ and $D_0(2400)D\pi$ couplings.

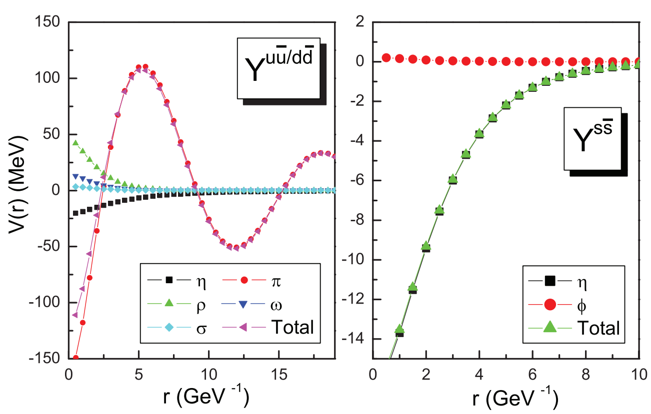

FIG. 2: (Color online.) The potentials of $Y^{s\bar{s}}$ (right-side diagram) and $Y^{u\bar{u}/d\bar{d}}$ (left-side diagram) with typical value $\Lambda = 1$ GeV. Here, we take $\beta = 0.9$, $\beta' = 1$, $g_\sigma = g'_\sigma = -0.76$, $h = -0.56 \pm 0.28$ following Refs. [21, 22].

In Fig. 3, we show the variation of the numerical result of the bound state solutions for $Y^{s\bar{s}}$ with the values of h and Λ, which indicates that there indeed exists a $D_{s0}(2317)\bar{D}_s + h.c.$ molecular charmonium corresponding to newly observed enhancement $Y(4274)$. Our numerical results overlap with the mass difference (~ -11 MeV) between $Y(4274)$ and the threshold of $D_{s0}(2317)\bar{D}_s$. The corresponding cutoff Λ lies in a reasonable range which is expected to be around 1-3 GeV.

We also find that the larger $|h|$ values make the corresponding Λ become smaller, *i.e.*, Λ tends to be around 1 GeV, which is fully consistent with the expected behavior of the potential of the S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ system.

Besides supporting the assignment of $Y(4274)$ as the S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ molecular state, our dynamical calculation also provides a novel approach to extract the h parameter, which encodes the important information of the $D_{s0}(2317)D_s\eta$ interaction and the underlying properties of $D_{s0}(2317)$ [25]. This coupling can not be extracted experimentally since the $D_{s0}(2317) \to D_s\eta$ decay is forbidden kinematically. Our result indicates that the $|h|$ value corresponding to the binding energy of the S-wave $D_{s0}(2317)\bar{D}_s+h.c.$ system consistent with mass difference (~ -11 MeV) is in the range $1.2 \sim 1.5$ associated with reasonable Λ value, which can be confirmed by further theoretical study.

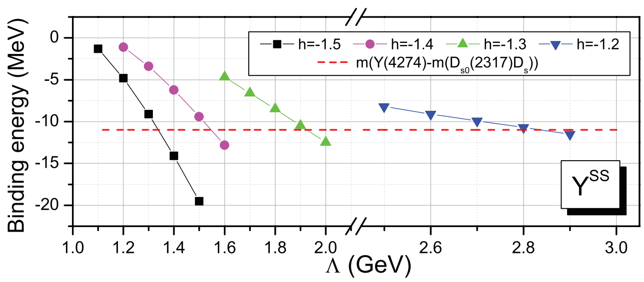

FIG. 3: (Color online.) The obtained bound state solutions of $Y^{s\bar{s}}$ system dependent on h values and Λ. Here, we also compare our result with the mass difference (red dashed line) between $Y(4274)$ and the threshold of $D_{s0}(2317)D_s$.

We extend the same formalism to the $Y^{u\bar{u}/d\bar{d}}$ system, where input parameter h for the $D_0(2400)D\pi$ coupling is constrained by the decay width of the $D_0(2400) \to D\pi$ to be $h = -0.56 \pm 0.2$ [21]. The binding energy of the $Y^{u\bar{u}/d\bar{d}}$ system is -9.85, -10.11, -10.23, -10.30, -10.34, -10.38, -10.42 MeV corresponding to the typical value of $\Lambda = 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5$ GeV, where the bound state solution of the $Y^{u\bar{u}/d\bar{d}}$ system is insensitive to Λ, which indicates the existence of the molecular cousin of the S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ molecular state, *i.e.*, an S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium. Thus, finding the evidence of S-wave $D_0(2400)\bar{D}+h.c.$ molecular charmonium can provide important support to the assignment of $Y(4274)$ as an S-wave $D_{s0}(2317)\bar{D}_s+h.c.$ molecular state. The important hidden-charm decay mode of the S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium is $J/\psi\omega$, which is the same as in the case of $Y(3930)$ [3, 4].

From the published experimental data of the $J/\psi\omega$ invariant mass spectrum [3, 4], we indeed notice an enhancement structure around 4.2 GeV just below the threshold of the $D_0(2400)\bar{D}$ pair as illustrated in Fig. 4, which is amazingly

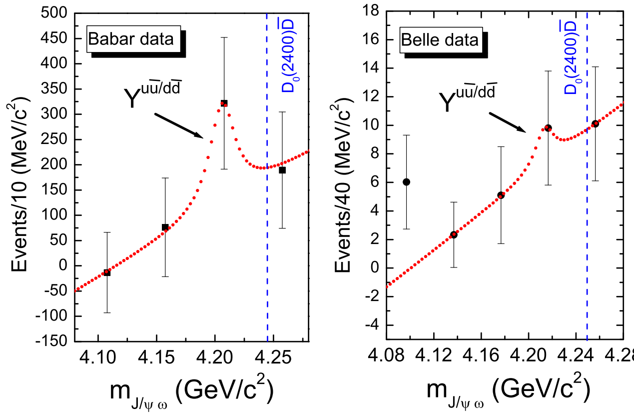

FIG. 4: The $J/\psi\omega$ invariant mass spectrum in the $B \to J/\psi\omega K$ decay announced by the Belle Collaboration [3] and the Babar Collaboration [4]. Here, the vertical blue dashed line denotes the threshold of $D_0(2400)\bar{D}$. The red dotted line is the fitting result.

consistent with our prediction of the S-wave $D_0(2400)\bar{D}+h.c.$ molecular charmonium. We expect further high-statistics measurement from future experiments to test our prediction of the S-wave $D_0(2400)\bar{D} + h.c.$ molecular charmonium.

As an S-wave $D_{s0}(2317)\bar{D}_s + h.c.$ molecular charmonium with $J^P = 0^-$, the decay modes of $Y(4274)$ include the hidden-charm decay mode $J/\psi\phi$ observed by CDF [1], the two-body P-wave open-charm decays $D_s\bar{D}_s^* + h.c.$ and $D_s^*\bar{D}_s^*$, the radiative decay $D_s^*\bar{D}_s\gamma + h.c.$, and the iso-spin violating three-body strong decay $D_s\bar{D}_s\pi^0$ via the $\eta - \pi^0$ mixing mechanism [2, 3]. Similarly $Y^{u\bar{u}/d\bar{d}}$ can decay into $J/\psi\omega$, $D\bar{D}^*+h.c.$, $D^*\bar{D}^*$, $D\bar{D}\pi$, $D^*\bar{D}\gamma + h.c.$ etc.

After figuring out the underlying structure of $Y(4274)$ and predicting its molecular cousin, we notice that there exist two event clusters around the ranges of $\Delta M \sim 1.27$ GeV and $1.4 < \Delta M < 1.5$ GeV marked by yellow and pink in Fig. 1, if we focus on the remaining CDF's data corresponding to $\Delta M > 1.24$ GeV. If these two event clusters are confirmed by future experiments, we might also try to understand them under the same framework of the molecular charmonium. Basing on the present low-statistic data [1], we speculate that the structure appearing at $\Delta M \sim 1.27$ is related to the $D_s\bar{D}'_{s1}(2460)$ or $D_s^*\bar{D}_{s0}(2317)$ system. The other one in the range $1.4 < \Delta M < 1.5$ GeV may result from the $D_s\bar{D}_{s1}(2536)$, $D_s\bar{D}_{s2}(2573)$, $D_s^*\bar{D}'_{s1}(2460)$ and $D_s^*\bar{D}_{s1}(2536)$ systems since the event cluster in the range $1.4 < \Delta M < 1.5$ GeV just overlaps with the corresponding thresholds (see Fig. 1 for more details). One may recall the similar situation before finding the evidence of $Y(4274)$ by CDF [1]. The CDF's data with an integrated luminosity of 2.7 fb^{-1} reported in Ref. [2] only displayed the event cluster at 4.27 GeV besides the evidence of $Y(4140)$. Confirming the above speculation by further experimental study of $J/\psi\phi$ invariant mass spectrum from B decay will not only test the molecular charmonium assignments of $Y(4140)$ and $Y(4274)$, but also improve our understanding of the line shapes appearing at hidden-charm invariant mass spectra.

In summary, the newly observed structure $Y(4274)$ in the

$J/\psi\phi$ invariant mass spectrum is first interpreted as the S-wave $D_s\bar{D}_{s0}(2317) + h.c.$ molecular charmonium well from the dynamical study of the system composed of the pseudoscalar and scalar charmed mesons. Furthermore, we predict the S-wave $D\bar{D}_0(2400) + h.c.$ molecular charmonium appearing as the cousin of $Y(4274)$, which is consistent with the enhancement structure around 4.2 GeV in the $J/\psi\omega$ invariant mass spectrum from B decay [2, 3]. Thus, the enhancement structures including the present $Y(4274)$, the previous $Y(4140)$ and $Y(3930)$ observed in the $J/\psi\phi$ [1, 2] and $J/\psi\omega$ [2, 3] invariant mass spectra respectively, can be accommodated well in the uniform framework of the molecular charmonium. In addition, we find two possible event clusters in the $J/\psi\phi$ invariant mass spectrum might related to the molecular charmonia, which can be tested by high-statistic experimental data in future experiment.

Acknowledgment

X.L. thanks Dr. Jun He for his help of fitting data. This project is supported by the National Natural Science Foundation of China under Grants No. 10705001, No. 11035006, No. 10947204, No. 10625521, No. 10721063, the Ministry of Science and Technology of China (2009CB825200), and the Ministry of Education of China (FANEDD under Grant No. 200924, DPFIHE under Grant No. 20090211120029, NCET under Grant No. NCET-10-0442, the Fundamental Research Funds for the Central Universities under Grant No. lzujbky-2010-69).

[1] K. Yi [CDF Collaboration], arXiv:1010.3470 [hep-ex].
[2] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102**, 242002 (2009) [arXiv:0903.2229 [hep-ex]].
[3] K. Abe *et al.* [Belle Collaboration], Phys. Rev. Lett. **94**, 182002 (2005) [arXiv:hep-ex/0408126].
[4] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **101**, 082001 (2008) [arXiv:0711.2047 [hep-ex]].
[5] X. Liu and S. L. Zhu, Phys. Rev. D **79**, 094026 (2009) [arXiv:0903.2529 [hep-ph]].
[6] X. Liu, Z. G. Luo, Y. R. Liu and S. L. Zhu, Eur. Phys. J. **C 61**, 411-428 (2009) [arXiv:0808.0073 [hep-ph]].
[7] N. Mahajan, Phys. Lett. B **679**, 228 (2009) [arXiv:0903.3107 [hep-ph]].
[8] Z. G. Wang, Eur. Phys. J. C **63**, 115 (2009) [arXiv:0903.5200 [hep-ph]].
[9] T. Branz, T. Gutsche and V. E. Lyubovitskij, Phys. Rev. D **80**, 054019 (2009) [arXiv:0903.5424 [hep-ph]].
[10] R. M. Albuquerque, M. E. Bracco and M. Nielsen, Phys. Lett. B **678**, 186 (2009) [arXiv:0903.5540 [hep-ph]].
[11] X. Liu, Phys. Lett. B **680**, 137 (2009) [arXiv:0904.0136 [hep-ph]].
[12] G. J. Ding, Eur. Phys. J. C **64**, 297 (2009) [arXiv:0904.1782 [hep-ph]].
[13] J. R. Zhang and M. Q. Huang, J. Phys. G **37**, 025005 (2010) [arXiv:0905.4178 [hep-ph]].
[14] E. van Beveren and G. Rupp, arXiv:0906.2278 [hep-ph].
[15] F. Stancu, arXiv:0906.2485 [hep-ph].
[16] X. Liu and H. W. Ke, Phys. Rev. D **80**, 034009 (2009) [arXiv:0907.1349 [hep-ph]].
[17] Z. G. Wang, Z. C. Liu and X. H. Zhang, Eur. Phys. J. C **64**, 373 (2009) [arXiv:0907.1467 [hep-ph]].
[18] N. V. Drenska, R. Faccini and A. D. Polosa, Phys. Rev. D **79**, 077502 (2009) [arXiv:0902.2803 [hep-ph]].
[19] R. Molina and E. Oset, Phys. Rev. D **80**, 114013 (2009) [arXiv:0907.3043 [hep-ph]].
[20] T. M. Yan, H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin and H. L. Yu, Phys. Rev. D **46**, 1148 (1992) [Erratum-ibid. D **55**, 5851 (1997)].
[21] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio and G. Nardulli, Phys. Rept. **281**, 145 (1997) [arXiv:hep-ph/9605342].
[22] W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D **68**, 054024 (2003) [arXiv:hep-ph/0305049].
[23] X. Liu, Y. R. Liu, W. Z. Deng and S. L. Zhu, Phys. Rev. D **77**, 034003 (2008) [arXiv:0711.0494 [hep-ph]]; Y. R. Liu, X. Liu, W. Z. Deng and S. L. Zhu, Eur. Phys. J. C **56**, 63 (2008) [arXiv:0801.3540 [hep-ph]]; X. Liu, Y. R. Liu, W. Z. Deng and S. L. Zhu, Phys. Rev. D **77**, 094015 (2008) [arXiv:0803.1295 [hep-ph]].
[24] L. L. Shen, X. L. Chen, Z. G. Luo, P. Z. Huang, S. L. Zhu, P. F. Yu and X. Liu, accepted by Eur. Phys. J. C, arXiv:1005.0994 [hep-ph].
[25] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **90**, 242001 (2003) [arXiv:hep-ex/0304021].