Role of Y(4630) in the pp[over ¯]→Λ_{c}Λ[over ¯]_{c} reaction near threshold

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Role of $Y(4630)$ in the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction near threshold

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We investigate the charmed baryon production reaction $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ in the effective Lagrangian approach. Besides the t-channel D^0 and D^{*0} mesons exchanges, the s-channel $Y(4630)$ meson exchange is taken into account. For the total cross sections, the D^0 and D^{*0} mesons provide minor background contributions, while the $Y(4630)$ state gives a clear peak structure with the magnitude of 10 μb at center of mass energy 4.63 GeV. Basing on the results, we suggest that the reaction of $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ can be used to search for the 1^{--} charmonium-like $Y(4630)$ state, and our predictions may be tested in the future by the $\bar{\text{P}}$ANDA facility.

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I. INTRODUCTION

A new charmonium-like $Y(4630)$, $J^{PC} = 1^{--}$, was firstly reported by the Belle collaboration in the exclusive $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ process, and its mass and width are 4634^{+8+5}_{-7-8} MeV and 92^{+40+10}_{-24-21} MeV, respectively [1]. After its discovery, various interpretations, such as conventional charmonium state [2, 3], tetraquark state [4–6], $\Lambda_c\bar{\Lambda}_c$ baryonium [7, 8] and threshold effect [9], were performed. The mechanism of $Y(4630)$ enhancement in $\Lambda_c\bar{\Lambda}_c$ electroproduction was also studied [10]. Recently, a series of investigations on the strong decay behaviors were proposed, which intended to reveal the inner structure of the $Y(4630)$ [11–13].

Above the $\Lambda_c\bar{\Lambda}_c$ threshold, another 1^{--} resonance $Y(4660)$, which mass and width are consistent within errors with the state $Y(4630)$, was observed in the initial state radiation process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ by the Belle collaboration [14], and confirmed by the BaBar collaboration after a long debate [15]. The explanations include conventional $c\bar{c}$ state [16, 17], $\psi(2S)f_0(980)$ molecule [18–20], hadro-charmonium [21], tetraquark state [4, 22, 23] and baryonium [24]. Although the $Y(4630)$ and $Y(4660)$ were observed in different processes, the similar masses and widths suggest that they could be the same state, which is also discussed in many theoretical works [5, 25, 26]. Other related studies are also performed [27–30], and a comprehensive review can be found in Ref. [31]. In the present work, we adopt the wildly accepted opinion that the $Y(4630)$ and $Y(4660)$ are regarded as the same state.

The theoretical works of the $Y(4630)$ mainly focus on the mass and decay width, and the production experiment is only limited in e^+e^- collision. In addition, the production of charmed baryon states in the $p\bar{p}$ collisions has been investigated within many theoretical models, such as the quark-diquark picture, a handbag approach, a quark-gluon string model which based on Regge asymptotics, meson-exchange model, and single-channel effective Lagrangian model [32–39].

Taking into account that the branching ratio of $Y(4630) \to p\bar{p}$ partial decay process was predicted to be several percent in Ref. [13], we suggest to search the $Y(4630)$ state in the reaction of $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$, where the intermediate state $Y(4630)$ is wished to play an important role. In the present work, we will study the reaction of $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ within the effective Lagrangian approach by taking into account the t-channel D and D^* mesons exchanges, the s-channel $Y(4630)$ contribution, and predict the total and differential cross sections of the reaction $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$. Our predictions **may be** tested by the $\bar{\text{P}}$ANDA facility, which has a maximum beam momenta 15 GeV of antiproton with high luminosity [40], and covers center-of-mass energies between 2.2 and 5.5 GeV [41], and **could** produce the $Y(4630)$ state.

This paper is organized as follows. We present the formalism and ingredients of the effective Lagrangian approach in Sec. II. The numerical results of total and differential cross sections and discussions are shown in Sec. III. Finally, a short summary is given in the last section.

II. FORMALISM AND INGREDIENTS

For the process $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$, we will take into account the basic tree level Feynman diagrams, depicted in Fig. 1, which include the t-channel D and D^* meson exchanges, the s-channel $Y(4630)$ term.

The relevant effective Lagrangians of the vertexes in Fig. 1 can be written as [13, 42, 43],

$$\mathcal{L}_{\Lambda_c pD} = ig_{\Lambda_c pD}\bar{\Lambda}_c\gamma_5 pD + \text{H.c.}, \tag{1}$$

$$\mathcal{L}_{\Lambda_c pD^*} = g_{\Lambda_c pD^*}\bar{\Lambda}_c\gamma^\mu pD^*_\mu + \text{H.c.}, \tag{2}$$

$$\mathcal{L}_{Y\Lambda_c\bar{\Lambda}_c} = g_{Y\Lambda_c\bar{\Lambda}_c}Y_\mu\bar{\Lambda}_c\gamma^\mu\Lambda_c, \tag{3}$$

$$\mathcal{L}_{Yp\bar{p}} = g_{Yp\bar{p}}Y_\mu\bar{p}\gamma^\mu p, \tag{4}$$

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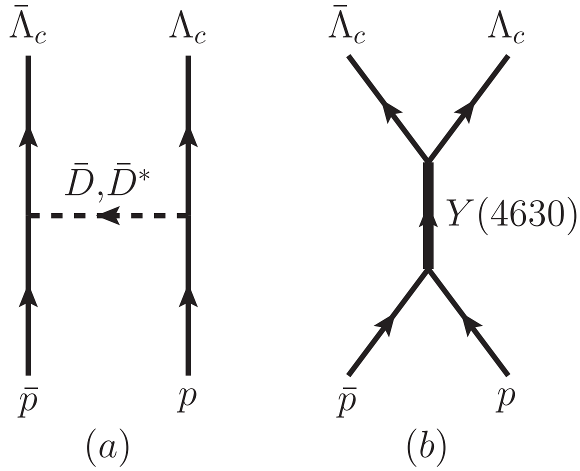

FIG. 1: Feynman diagrams for the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction. a) the t-channel D and D^* meson exchanges, b) the s-channel $Y(4630)$ term.

where the coupling constants of $\Lambda_c pD$ and $\Lambda_c pD^*$ interactions are taken as $g_{\Lambda_c pD} = 10.7^{+5.3}_{-4.3}$ and $g_{\Lambda_c pD^*} = -5.8^{+2.1}_{-2.5}$ [38, 44]. The couplings of $Y\Lambda_c\bar{\Lambda}_c$ and $Yp\bar{p}$ can be obtained from their partial decay widths. In Ref. [13], assuming the $Y(4630) \to \Lambda_c\bar{\Lambda}_c$ is dominant decay, the branching ratios of $p\bar{p}$ final state are predicted to be 0.037 and 0.062 for different cut off values within the effective Lagrangian approach. In this work, we adopt the same assumption of the $\Lambda_c\bar{\Lambda}_c$ being the dominant decay channel, and take the $p\bar{p}$ decay ratio being 1%. With the effective Lagrangians above, the partial decay widths can be expressed as,

$$\Gamma(Y(4630) \to \Lambda_c\bar{\Lambda}_c) = \frac{g^2_{Y\Lambda_c\bar{\Lambda}_c}(m_Y^2 + 2m^2_{\Lambda_c})|\vec{p}^{\,\rm cm}_{\Lambda_c}|}{6\pi m_Y^2}, \quad (5)$$

$$\Gamma(Y(4630) \to p\bar{p}) = \frac{g^2_{Yp\bar{p}}(m_Y^2 + 2m_p^2)|\vec{p}^{\,\rm cm}_p|}{6\pi m_Y^2}, \quad (6)$$

where m_Y, m_{Λ_c} and m_p are the masses of $Y(4630)$, $\Lambda_c/\bar{\Lambda}_c$ and (anti)proton [45], respectively, and $\vec{p}^{\,\rm cm}_{\Lambda_c}$ ($\vec{p}^{\,\rm cm}_p$) is the 3-momentum of the initial proton (final Λ_c) in the rest frame of $p\bar{p}$ ($\Lambda_c\bar{\Lambda}_c$). With the experimental data of the total decay width $\Gamma_Y = 92$ MeV[1], we can obtain $g_{Y\Lambda_c\bar{\Lambda}_c} = 1.78$, and $g_{Yp\bar{p}} = 0.087$.

Since the hadrons are not point-like particles, the form factors are needed to describe the off-shell effects. We adopt here the monopole form factor used in many previous works for the t-channel D and D^* interaction vertices:

$$\mathcal{F}(q^2, m^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}, \quad (7)$$

where q, m and Λ are the the four-momentum, mass, and cut-off parameter for the exchanged mesons, respectively. The cut-off parameter Λ can be parametrized as [46]

$$\Lambda = m + \alpha\Lambda_{\rm QCD}, \quad (8)$$

with $\Lambda_{\rm QCD} = 220$ MeV, and the dimensionless parameter α is of order unity. The α mainly varies in the range of $0.5 \sim 1.5$ in literature [46–48], and for the D and D^* mesons exchanges, the large value of $\alpha = 1.5$ is employed in the present work. Indeed, the value of α does not affect the signal of the $Y(4630)$ in the reaction $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$, we will discuss this later. The form factor for s-channel $Y(4630)$ state is taken in the form advocated in Refs. [49–55],

$$F_Y(q^2, m^2) = \frac{\Lambda_Y^4}{\Lambda_Y^4 + (q^2 - m_Y^2)^2}, \quad (9)$$

where the cut-off parameters $\Lambda_Y = 500$ MeV for the $Y(4630)$ state is used [52–54].

Then, according to the Feynman rules, the scattering amplitudes for the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction can be obtained straightforwardly with the above effective Lagrangians,

$$\begin{aligned}\mathcal{M}_D &= g^2_{\Lambda_c pD}\mathcal{F}^2(q_D^2, m_D^2)\bar{\upsilon}(p_1, s_1)\gamma_5\upsilon(p_3, s_3)\\ &\quad G_D\bar{u}(p_4, s_4)\gamma_5 u(p_2, s_2),\end{aligned} \quad (10)$$

$$\begin{aligned}\mathcal{M}_{D^*} &= -g^2_{\Lambda_c pD^*}\mathcal{F}^2(q^2_{D^*}, m^2_{D^*})\bar{\upsilon}(p_1, s_1)\gamma_\mu\upsilon(p_3, s_3)\\ &\quad G^{\mu\nu}_{D^*}\bar{u}(p_4, s_4)\gamma_\nu u(p_2, s_2),\end{aligned} \quad (11)$$

$$\begin{aligned}\mathcal{M}_Y &= -g_{Y\Lambda_c\bar{\Lambda}_c}g_{Yp\bar{p}}F_Y(q_Y^2, m_Y^2)\bar{\upsilon}(p_1, s_1)\gamma_\mu\upsilon(p_2, s_2)\\ &\quad G^{\mu\nu}_Y\bar{u}(p_4, s_4)\gamma_\nu u(p_3, s_3),\end{aligned} \quad (12)$$

where $s_i (i = 1, 2, 3, 4)$ and $p_i (i = 1, 2, 3, 4)$ represent the spin projection and four-momentum of the initial or final states, respectively; $q_{D^{(*)}} = p_3 - p_1$ is the momentum of D^0 (D^{*0}) state. $q_Y = p_1 + p_2$ is the momentum of the $Y(4630)$ state. G_D, G_{D^*} and G_Y are the propagators for the D, D^*, and $Y(4630)$ states.

The D meson propagator can be written as

$$G_D = \frac{i}{q^2 - m_D^2}, \quad (13)$$

and the one of vector meson D^* is

$$G^{\mu\nu}_{D^*} = -i\frac{g^{\mu\nu} - q^\mu q^\nu/m^2_{D^*}}{q^2 - m^2_{D^*}}. \quad (14)$$

The propagator for $Y(4630)$ 1^{--} state can be written as,

$$G_Y = -i\frac{g^{\mu\nu} - q^\mu q^\nu/m_Y^2}{q^2 - m_Y^2 + im_Y\Gamma_Y}, \quad (15)$$

where $\Gamma_Y = 92$ MeV is the total width of the $Y(4630)$ meson.

The total amplitude for the process $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ are the coherent sum of $\mathcal{M}_D$, $\mathcal{M}_{D^*}$, and $\mathcal{M}_Y$,

$$\mathcal{M} = \mathcal{M}_D + \mathcal{M}_{D^*} + \mathcal{M}_Y. \quad (16)$$

The differential cross section can be easily given as,

$$\frac{d\,\sigma}{d\cos\theta} = \frac{1}{32\pi s}\frac{|\vec{p}_3^{\,\rm c.m.}|}{|\vec{p}_1^{\,\rm c.m.}|}\left(\frac{1}{4}\sum_{s_1,s_2,s_3,s_4}|\mathcal{M}|^2\right) \quad (17)$$

where s is the invariant mass square of the $p\bar{p}$ system. θ denotes the angle of the outgoing baryon Λ_c relative to the beam direction in the c.m. frame, while $\vec{p}_1^{\,\mathrm{c.m.}}$ and $\vec{p}_3^{\,\mathrm{c.m.}}$ are the 3-momentum of the initial p and final Λ_c in the c.m. frame.

III. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we will present our results for the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction within the effective Lagrangian model.

We show the total cross sections for the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction from threshold up to 5 GeV of c.m. energy in Fig. 2, where the green dashed, blue dash-dotted, and pink dotted lines represent the contributions of the s-channel $Y(4630)$ terms, t-channel D and D^* mesons exchanges, respectively. The red solid line stands for the total cross section. The t-channel D^* meson exchange provides a larger contribution than D meson exchange, which is consistent with the result of Ref. [39]. By including the contribution of s-channel, the total cross section has a clear peak structure at the c.m. energy 4630 MeV. The magnitude of the peak is of order 10 μb, which **may be** measured in the future by the $\bar{\mathrm{P}}$ANDA facility with high luminosity.

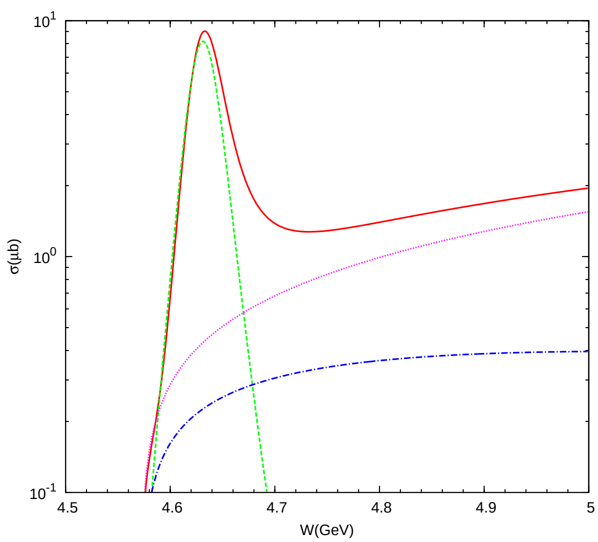

FIG. 2: (online color) Cross section of the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction as a function of $p\bar{p}$ invariant mass from threshold up to 5 GeV. The green dashed, blue dash-dotted, and pink dotted lines represent the contributions of the s-channel $Y(4630)$ terms, t-channel D and D^* mesons exchanges, respectively. The red solid line stands for the total cross section.

It is interesting to note that for the $Y(4630)$ state, a relatively small cut off value is used, which seems more suitable for heavy hadron production processes [52–54]. As this value increases, the contributions of $Y(4630)$ will become larger and the peak structure is also clear. In fact, the form factor is approximate equal to unity near the $Y(4630)$ resonance region, since the $s - M_Y^2 \sim 0$. Thus, whatever value of the cut-off for the $Y(4630)$ state is taken, its signal is always clear, which is one of the reasons why we suggest to search the $Y(4630)$ state in the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction.

We show the total cross section in Fig. 3 by taking into account the uncertainties of the total width of $Y(4630)$ ($50 \sim 140$ MeV). As we can see, the peak structure becomes broader for the small width, and narrower for the large width.[1]

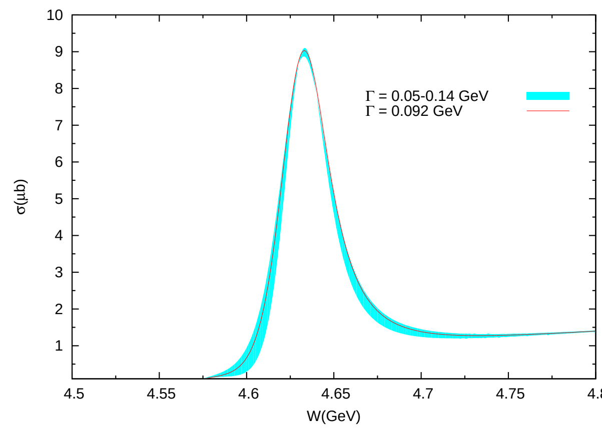

FIG. 3: (online color) Total cross section of the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction for the decay width of $Y(4630)$ varying from 50 to 140 MeV.

The dependence of the total cross section on the parameter α is shown in Fig. 4. It can be seen that the contributions of t-channel exchange decrease as the parameter α decreases. In this work, we have shown that even a large $\alpha = 1.5$ is used, the structure of the $Y(4630)$ is still very clear.

[1] In Fig. 3, the values of the peaks for different widths are also similar, which is because the propagator of $Y(4630)$ with a larger width leads to a broader and lower peak, but the larger couplings caused by a larger width lead to a higher peak.

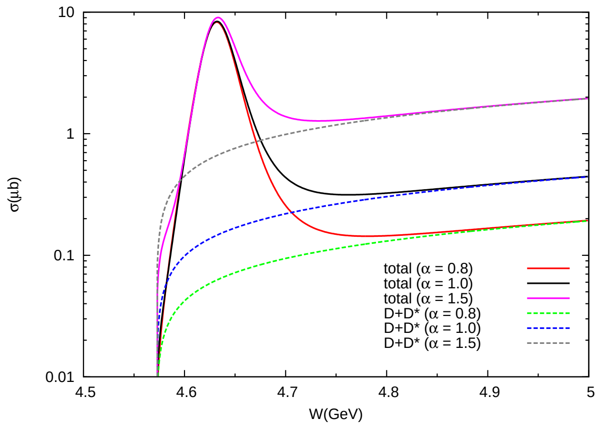

FIG. 4: (online color) Total cross section of the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction varies with parameter α.

In this work, we calculate the couplings of $Y(4630)$ basing on the result of Ref. [13], where the branching ratio is predicted in the theoretical model and the tensor term of D^* exchange is neglected. For the consistence, we also neglect the tensor term in Eq. (2) in this work. However, we still show the result by including the tensor term in the t-channel D^* meson exchange in Fig. 5 with the same branching as that in Fig. 2. As we can see, the t-channel D^* exchange gives a larger contribution, and there is still a small peak structure around 4.63 GeV. It should be noted that we need to re-determinate the value of branching ratio if the tensor term is taken into account, which could be discussed in the future with more experimental data.

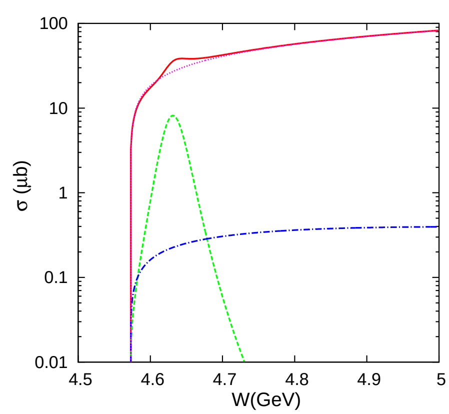

FIG. 5: (online color) Total cross section of the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction by taking into account the tensor term in Eq. (2), but without the changing of the $Y(4630)$ couplings. The explanations of the curves are same as that of Fig. 2.

Finally, we show the differential cross sections of $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction in Fig. 6. For the $p\bar{p}$ invariant mass from 4.6 to 4.8 GeV, the contributions of the t-channel D and D^* exchanges have the forward distributions, while the ones of the $Y(4630)$ are flat. Around the energy of 4.63 GeV, the $Y(4630)$ plays the dominate role, and its contribution can be ignored above 4.7 GeV. The bands show the results by taking into account the uncertainties of the decay width of $Y(4630)$ ($50 \sim 140$ MeV), from which we can see that the error of the total width of $Y(4630)$ only has a small influence on the differential cross sections around $W = 4.63$ GeV. Thus, the differential cross sections predicted in our model are flatter around the 4.63 GeV than that above 4.7 GeV, which will give a signature of the resonance state $Y(4630)$.

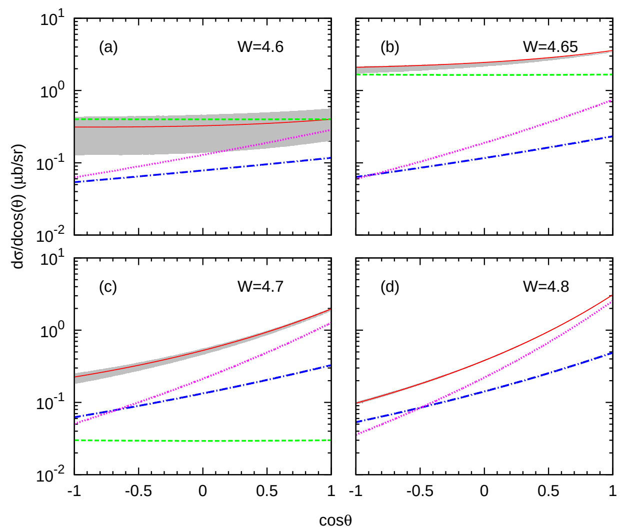

FIG. 6: Differential cross section of the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction as a function of cosθ. The explanations of the curves are same as that of Fig. 2. The bands stand for the results by taking into account the uncertainties of the decay width of $Y(4630)$ ($50 \sim 140$ MeV).

IV. SUMMARY

Considering the $J^{PC} = 1^{--}$ charmonium-like state $Y(4630)$ have a sizeable coupling to the $p\bar{p}$ according the prediction of Ref.[13], we suggest to search the $Y(4630)$ state in the reaction of $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ in this work.

Within the effective Lagrangian approach, we have phenomenologically investigated the $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$ reaction. Besides the background contributions of the t-channel D and D^* mesons exchanges, we have also included the s-channel $Y(4630)$ contribution. We have presented the total cross sections and the differential cross sections for this process. Our results show that close to the threshold of $p\bar{p}$ collision, the $Y(4630)$ state plays an important role, comparing to the background terms of the t-channel D and D^* mesons exchanges, and a clear bump structure with the magnitude of 10 μb appears. Our predictions may be tested in the future by the $\bar{\text{P}}$ANDA facility, which has a maximum beam momenta 15 GeV of antiproton with high luminosity [40], and could produce the $Y(4630)$ state.

Acknowledgments

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[1] G. Pakhlova *et al.* [Belle Collaboration], Phys. Rev. Lett. **101**, 172001 (2008).
[2] A. M. Badalian, B. L. G. Bakker and I. V. Danilkin, Phys. Atom. Nucl. **72**, 638 (2009).
[3] J. Segovia, D. R. Entem and F. Fernandez, arXiv:0810.2875.
[4] L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D **89**, 114010 (2014).
[5] G. Cotugno, R. Faccini, A. D. Polosa and C. Sabelli, Phys. Rev. Lett. **104**, 132005 (2010).
[6] S. J. Brodsky, D. S. Hwang and R. F. Lebed, Phys. Rev. Lett. **113**, no. 11, 112001 (2014).
[7] N. Lee, Z. G. Luo, X. L. Chen and S. L. Zhu, Phys. Rev. D **84**, 014031 (2011).
[8] Y. D. Chen and C. F. Qiao, Phys. Rev. D **85**, 034034 (2012) .
[9] E. van Beveren, X. Liu, R. Coimbra and G. Rupp, Europhys. Lett. **85**, 61002 (2009).
[10] Y. A. Simonov, Phys. Rev. D **85**, 105025 (2012).
[11] X. Liu, H. W. Ke, X. Liu and X. Q. Li, arXiv:1601.00762.
[12] X. Liu, H. W. Ke, X. Liu and X. Q. Li, arXiv:1602.00226.
[13] X. D. Guo, D. Y. Chen, H. W. Ke, X. Liu and X. Q. Li, Phys. Rev. D **93**, no. 5, 054009 (2016).
[14] X. L. Wang *et al.* [Belle Collaboration], Phys. Rev. Lett. **99**, 142002 (2007).
[15] J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D **89**, no. 11, 111103 (2014).
[16] G. J. Ding, J. J. Zhu and M. L. Yan, Phys. Rev. D **77**, 014033 (2008).
[17] B. Q. Li and K. T. Chao, Phys. Rev. D **79**, 094004 (2009).
[18] F. K. Guo, C. Hanhart and U. G. Meissner, Phys. Lett. B **665**, 26 (2008).
[19] F. K. Guo, C. Hanhart, and Ulf-G. Meissner, Phys. Rev. Lett. **102**, 242004 (2009).
[20] R. M. Albuquerque, M. Nielsen and R. R. da Silva, Phys. Rev. D **84**, 116004 (2011).
[21] S. Dubynskiy and M. B. Voloshin, Phys. Lett. B **666**, 344 (2008).
[22] D. Ebert, R. N. Faustov and V. O. Galkin, Eur. Phys. J. C **58**, 399 (2008).
[23] W. Chen and S. L. Zhu, Phys. Rev. D **83**, 034010 (2011).
[24] C. F. Qiao, J. Phys. G **35**, 075008 (2008).
[25] D. V. Bugg, J. Phys. G **36**, 075002 (2009).
[26] F. K. Guo, J. Haidenbauer, C. Hanhart, and Ulf-G. Meissner, Phys. Rev. D **82**, 094008 (2010).
[27] M. Cleven, F. K. Guo, C. Hanhart, Q. Wang and Q. Zhao, Phys. Rev. D **92**, no. 1, 014005 (2015).
[28] D. Y. Chen, X. Liu and T. Matsuki, Phys. Rev. Lett. **110**, no. 23, 232001 (2013).
[29] D. Y. Chen, X. Liu and T. Matsuki, J. Phys. G **42**, no. 1, 015002 (2015).
[30] D. Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D **93**, no. 3, 034028 (2016).
[31] H. X. Chen, W. Chen, X. Liu and S. L. Zhu, arXiv:1601.02092.
[32] P. Kroll, B. Quadder and W. Schweiger, Nucl. Phys. B **316**, 373 (1989).
[33] A. B. Kaidalov and P. E. Volkovitsky, Z. Phys. C **63**, 517 (1994).
[34] A. I. Titov and B. Kampfer, Phys. Rev. C **78**, 025201 (2008).
[35] A. T. Goritschnig, P. Kroll and W. Schweiger, Eur. Phys. J. A **42**, 43 (2009).
[36] J. Haidenbauer and G. Krein, Phys. Lett. B **687**, 314 (2010).
[37] J. Haidenbauer and G. Krein, Few Body Syst. **50**, 183 (2011).
[38] A. Khodjamirian, C. Klein, T. Mannel and Y. M. Wang, Eur. Phys. J. A **48**, 31 (2012).
[39] R. Shyam and H. Lenske, Phys. Rev. D **90**, no. 1, 014017 (2014).
[40] U. Wiedner, Prog. Part. Nucl. Phys. **66**, 477 (2011).
[41] G. Boca [PANDA Collaboration], EPJ Web Conf. **95**, 01001 (2015). doi:10.1051/epjconf/20159501001
[42] J. J. Xie, Y. B. Dong and X. Cao, Phys. Rev. D **92**, no. 3, 034029 (2015).
[43] J. He, Z. Ouyang, X. Liu and X. Q. Li, Phys. Rev. D **84**, 114010 (2011).
[44] A. Khodjamirian, C. Klein, T. Mannel and Y.-M. Wang, JHEP **1109**, 106 (2011).
[45] K. A. Olive *et al.* (Particle Data Group Collaboration), Review of Particle Physics, Chin. Phys. C **38**, 090001 (2014).
[46] Q. Y. Lin, X. Liu and H. S. Xu, Phys. Rev. D **90**, no. 1, 014014 (2014).
[47] D. Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D **87**, no. 5, 054006 (2013).
[48] D. Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D **90**, no. 3, 034019 (2014).
[49] T. Feuster and U. Mosel, Phys. Rev. C **58**, 457 (1998)
[50] G. Penner and U. Mosel, Phys. Rev. C **66**, 055211 (2002)
[51] V. Shklyar, H. Lenske and U. Mosel, Phys. Rev. C **72**, 015210 (2005)
[52] S. H. Kim, S. I. Nam, Y. Oh, and H. C. Kim, Phys. Rev. D **84**, 114023 (2011).
[53] Q. Wang, X. H. Liu and Q. Zhao, Phys. Rev. D **92**, 034022 (2015).
[54] Q. F. Lü, X. Y. Wang, J. J. Xie, X. R. Chen and Y. B. Dong, Phys. Rev. D **93**, no. 3, 034009 (2016).
[55] R. Shyam and H. Lenske, Phys. Rev. D **93**, no. 3, 034016 (2016).