Exploration of charmed pentaquarks

S. M. Gerasyuta† and V. I. Kochkin‡

Department of Physics, St. Petersburg State Technical University, Institutski Per. 5, St. Petersburg 194021, Russia

Xiang Liu†

1Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China
2School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China

In this work, we explore the charmed pentaquarks, where the relativistic five-quark equations are obtained by the dispersion relation technique. By solving these equations with the method based on the extraction of the leading singularities of the amplitudes, we predict the mass spectrum of charmed pentaquarks with $J^P = 1/2^\pm$ and $3/2^\pm$, which is valuable to further experimental study of charmed pentaquark.

PACS numbers: 11.55.Fv, 11.80.Jy, 12.39.Ki, 12.39.Mk

I. INTRODUCTION

Exploring and investigating exotic states, which include glueball, hybrid state and multiquark states, are an intriguing research topic in particle physics. With more and more observations of new hadronic states, there were extensive discussions of whether these observed new hadronic states are good candidates of exotic states (see Refs. [1] [2] for a recent review). Studying the hadronic configuration beyond the conventional meson and baryon can make our knowledge of non-perturbative QCD be abundant.

In 2013, the BESIII Collaboration announced the observation of the charged charmonium-like structure $Z_0(3900)$ in the $J/\psi^\pm$ invariant mass spectrum of $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4.26$ GeV [3]. $Z_0(3900)$ can be a good candidate of the $D\bar{D}^*$ molecular state [4], which is as one of the four-quark matters. If four-quark matter is possible existing in nature, we naturally conjecture whether there exist pentaquark states.

In 2003, the $\Upsilon(1S) \rightarrow K^+K^-X$ reaction was studied and a peak was found in the $K^+n$ invariant mass spectrum around 1540 MeV, which was identified as a signal for a pentaquark with positive strangeness, the "$\Theta^+(1540)$" [6]. The unexpected finding lead to a large number of poor statistic experiments where a positive signal was also found, but gradually an equally big number of large statistic experiments showed no evidence for such a peak. A comprehensive review of these developments was done in [7], where one can see the relevant literature on the subject, as well as in the devoted section of Particle Data Group (PDG) [8].

Although the signal of $\Theta^+(1540)$ was not confirmed in experiment, searching for pentaquark is still an important task [9]. Thus, we need to carry out further theoretical study of pentaquark, which can provide us more abundant information of possible pentaquark. We also notice that most of new hadronic states were observed in the charm-$\tau$ energy region. This fact shows that the charm-$\tau$ energy region should be a suitable platform to study pentaquark. Especially, the $Z_0(3900)$ observation boosts our confidence to study heavy flavor pentaquark again.

In this work, we focus on the charmed pentaquark states with $J^P = 1/2^\pm, 3/2^\pm$, which are composed of a charm antiquark and four light quarks. Firstly, we need to construct relativistic five-quark equations, which contain the $u, d,$ and $c$ quarks. And then, the masses of these discussed pentaquarks can be determined by the poles of these amplitudes, where the constituent quark involved in our calculation is the color triplet and the quark amplitudes obey the global color symmetry. As the main task of this work, we need to perform the calculation of the pentaquark amplitudes which contain the contribution of four subamplitudes: molecular subamplitude $BM$, $D\bar{D}$, $Mqqq$ subamplitudes and $Dqqq$ subamplitude ($D$ denotes the diquark state, $B$ and $M$ are the baryon and meson states), where the relativistic generalization of five-quark Faddeev-Yakubovsky equations is constructed in the form of the dispersion relation [10]. Finally, we can get the masses of the low-lying charmed pentaquarks, which provide valuable information to further experimental search for these predicted charmed pentaquarks.

Our paper is organized as follows. After this introduction, we present the five-quark amplitudes relevant to these discussed charmed pentaquarks. In Sec. [11] we show the numerical results. The last section is devoted to a summary.

II. FIVE-QUARK AMPLITUDES FOR THE CHARMED PENTAQUARKS

In the following, we introduce how to get the relativistic five-quark amplitudes for the charmed pentaquarks, where we adopt the dispersion relation technique. Due to the rules of $1/N_c$ expansion [11], we only need to consider planar diagrams, while the other diagrams can be neglected. By summing over all possible subamplitudes which correspond to the division of complete system into subsystems smaller number of particles, we can obtain the total amplitude.

In general, a five-particle amplitude ($\mathcal{A}$) can be expressed as the sum of ten subamplitudes ($\mathcal{A}_{ij}$ ($i = 1, 2, 3, 4, \ j =$...
\[ A = A_{12} + A_{13} + A_{14} + A_{15} + A_{23} + A_{24} + A_{25} + A_{34} + A_{35} + A_{45}, \]

where \( A_{ij} \) denotes the subamplitude from the pair interaction of particles \( i \) and \( j \) in a five-particle system.

For the sake of simplifying the calculation, we take the relativistic generalization of the Faddeev-Yakubovsky approach. With the \( uuudc \) system as an example, we introduce how to obtain \( A_{12} \). Firstly, we need to construct the five-quark amplitude of the \( uuudc \) system, where only pair interaction with the quantum numbers of six and seven subamplitudes, respectively. Here, the coefficients can be obtained by the permutation of quarks \( \{123\} \) in the \( uuudc \) and \( uuddc \) systems, which are shown in Fig. 1. For the cases of the \( uuudc \) and \( uuddc \) systems, there are six and seven subamplitudes, respectively. Here, the coefficients can be obtained by the permutation of quarks \( \{123\} \).

In the following, we need to further illustrate how to write out the subamplitudes \( A_{1}(s, s_{1234}, s_{12}, s_{34}), A_{2}(s, s_{1234}, s_{25}, s_{34}), A_{3}(s, s_{1234}, s_{13}, s_{34}), A_{4}(s, s_{1234}, s_{25}, s_{234}) \), and \( A_{5}(s, s_{1234}, s_{13}, s_{34}) \), which are in the form of a dispersion relation. Firstly, we need to define the amplitudes of quark-quark and quark-antiquark interaction \( b_{n}(s_{ik}) \). With the help of four-fermion interaction with quantum numbers of the gluon \( [16] \), we can calculate the amplitudes \( q \bar{q} \rightarrow q \bar{q} \) through the dispersion N/D method. Thus, the pair quarks amplitude can be expressed as \( [16] \)

\[ b_{n}(s_{ik}) = \frac{G_{n}^{2}(s_{ik})}{1 - B_{n}(s_{ik})}, \quad (2) \]

\[ B_{n}(s_{ik}) = \int_{(m_{i} + m_{k})^{2}}^{s_{ik}} \frac{ds'_{ik}}{\pi} \rho_{n}(s'_{ik}) G_{n}^{2}(s'_{ik}), \quad (3) \]

where \( s_{ik} \) denotes the two-particle subenergy squared. And \( s_{ik} \) is the energy squared of particles \( i, j \), while \( s_{ijkl} \) is the four-particle subenergy squared. In addition, we also define \( s \) as the system total energy squared.

We obtain the concrete forms of \( A_{i} \) \((i = 1, 2, 3, 4)\), i.e.,

\[ A_{1}(s, s_{1234}, s_{12}, s_{34}) = \frac{A_{1}B_{2}(s_{12})B_{2}(s_{34})}{[1 - B_{2}(s_{12})][1 - B_{2}(s_{34})]} + 6f_{2}(3, 2)A_{4}(s, s_{1234}, s_{23}', s_{23}) + 2f_{2}(3, 2)A_{3}(s, s_{1234}, s_{13}', s_{13}) + 2f_{3}(3)A_{3}(s, s_{1234}, s_{13}', s_{13}) + 2f_{2}(1, 2)A_{4}(s, s_{1234}, s_{23}', s_{23}), \]

\[ A_{2}(s, s_{1234}, s_{25}, s_{34}) = \frac{A_{2}B_{2}(s_{25})B_{2}(s_{34})}{[1 - B_{2}(s_{25})][1 - B_{2}(s_{34})]} + 12f_{2}(2, 2)A_{4}(s, s_{1234}, s_{23}', s_{23}) + 8f_{2}(1)A_{3}(s, s_{1234}, s_{25}, s_{25}). \]

\[ A_{3}(s, s_{1234}, s_{13}, s_{34}) = \frac{A_{3}B_{2}(s_{12})}{1 - B_{2}(s_{12})} + 12f_{3}(3)A_{1}(s, s_{1234}, s_{13}', s_{13}), \quad (6) \]

\[ A_{4}(s, s_{1234}, s_{25}, s_{234}) = \frac{A_{4}B_{2}(s_{25})}{1 - B_{2}(s_{25})} + 4f_{2}(1, 2)A_{2}(s, s_{1234}, s_{25}', s_{23}), \quad (7) \]

where \( \lambda_{i} \) denotes the current constants. In addition, the integral operators \( f_{1}(l), f_{2}(l, p) \), and \( f_{3}(l, p) \) are introduced, where their expressions can be found in Appendix. Taking the same treatment as that given in Ref. [18], where we pass from the integration over the cosines of the angles to the integration over the subenergies, we can extract two-particle singularities in the amplitudes \( A_{1}(s, s_{1234}, s_{12}, s_{34}), A_{2}(s, s_{1234}, s_{25}, s_{34}), A_{3}(s, s_{1234}, s_{13}, s_{34}), A_{4}(s, s_{1234}, s_{25}, s_{234}) \), and \( A_{5}(s, s_{1234}, s_{13}, s_{34}) \), respectively.
FIG. 2: The graphic representation of the equations for the five-quark subamplitudes for the \( uuud \) and \( ududc \) systems. Here, the \( c \) quark is denoted by the lines with arrow. There are six and seven diagrams for the \( uuud \) and \( ududc \) systems, respectively.

\[
A_3(s, s_{1234}, s_{13}, s_{134}), \text{ and } A_4(s, s_{1234}, s_{24}, s_{234}):
\]

\[
A_1(s, s_{1234}, s_{12}, s_{34}) = \frac{\alpha_1(s, s_{1234}, s_{12}, s_{34})B_1(s_{12})B_2(s_{34})}{[1 - B_1(s_{12})][1 - B_2(s_{34})]},
\]

\[
A_2(s, s_{1234}, s_{25}, s_{34}) = \frac{\alpha_2(s, s_{1234}, s_{25}, s_{34})B_2(s_{25})B_2(s_{34})}{[1 - B_2(s_{25})][1 - B_2(s_{34})]},
\]

\[
A_3(s, s_{1234}, s_{13}, s_{134}) = \frac{\alpha_3(s, s_{1234}, s_{13}, s_{134})B_1(s_{13})}{1 - B_3(s_{13})},
\]

\[
A_4(s, s_{1234}, s_{24}, s_{234}) = \frac{\alpha_4(s, s_{1234}, s_{24}, s_{234})B_2(s_{24})}{1 - B_3(s_{24})}.
\]

Here, we want to further specify that we do not extract the three-particle and four-particle singularities, which are weaker than the two-particle singularities. In addition, we also adopt the classification of singularities suggested in Ref. [19]. As the smooth functions of \( s_0, s_{ijk}, s_{ijkl}, \) and \( s, \) \( \alpha_1(s, s_{1234}, s_{12}, s_{34}), \) \( \alpha_2(s, s_{1234}, s_{25}, s_{34}), \) \( \alpha_3(s, s_{1234}, s_{13}, s_{134}) \) and \( \alpha_4(s, s_{1234}, s_{24}, s_{234}) \) can be expanded in a series in the singularity point, where only the first term of this series should be employed further. Thus, we further define the reduced amplitudes \( \alpha_1, \alpha_2, \alpha_3, \) and \( \alpha_4, \) and the B-functions in the middle point of the physical region of Dalitz-plot at the point \( s_0, \) i.e.,

\[
s^k_0 = s_0 = \frac{s + 3 \sum_{i=1}^{5} m_i^2}{0.25 \sum_{i,k=1,i\neq k}^{5} (m_i + m_k)^2}, \tag{8}
\]

\[
s_{123} = 0.25 s_0 \sum_{i,k=1,i\neq k}^{3} (m_i + m_k)^2 - \sum_{i=1}^{3} m_i^2, \tag{9}
\]
\[ s_{1234} = 0.25 s_0 \sum_{i,k=1,i\neq k}^4 (m_i + m_k)^2 - 2 \sum_{i=1}^4 m_i^2. \]  
(10)

Then, we replace the integral Eqs. (4)-(7) corresponding to the diagrams in Fig. 1 by the following algebraic equations

\[
\begin{align*}
\alpha_1 &= \lambda_1 + 6\alpha_4 J_2(3, 2, 2) + 2\alpha_3 J_2(3, 2, 3) + 2\alpha_3 J_1(3, 3) \\
&\quad + 2\alpha_4 J_1(3, 2) + 4\alpha_4 J_1(2, 2), \\
\alpha_2 &= \lambda_2 + 12\alpha_4 J_2(2, 2, 2) + 8\alpha_3 J_1(2, 3), \\
\alpha_3 &= \lambda_3 + 12\alpha_4 J_3(3, 3, 2), \\
\alpha_4 &= \lambda_4 + 4\alpha_4 J_3(2, 2, 2) + 4\alpha_1 J_3(2, 2, 3),
\end{align*}
\]
respectively. Here, the definitions of the functions \( J_i(l, p), J_2(l, p, r), J_3(l, p, r) \) \((l, p, r = 1, 2, 3)\) are listed in Appendix.

Finally, we have the function like

\[ \alpha_i(s) = F_i(s, \lambda_i)/D(s), \]
where the masses of these discussed systems can be determined by zeros of \( D(s) \) determinants. And, \( F_i(s, \lambda_i) \) denotes the function of \( s \) and \( \lambda_i \), which determines the contribution of subamplitude.

### III. NUMERICAL RESULTS

In Sec. [11] the involved parameters in our model include quark mass \( m_{ud,d} = 439 \) MeV and \( m_c = 1640 \) MeV, where we effectively take into account the contribution of the confinement potential in obtaining the spectrum of charmed pentaquarks. The adopted value of cutoff \( \Lambda = 10 \), which coincides with that taken in Ref. [20, 21]. In addition, a dimensionless parameter \( g \), which is the gluon coupling constant, is introduced in our calculation. We notice that the mass of charmed pentaquark with both configuration \( D_s^+ N (udud\bar{c}) \) and quantum number \((I)J^P = (0)\frac{3}{2}^+\) was calculated through the 
\[ \sum_{i,k=1,i\neq k}^4 (m_i + m_k)^2 - 2 \sum_{i=1}^4 m_i^2. \]

\[
\begin{align*}
\alpha_1 &= \lambda_1 + 6\alpha_4 J_2(3, 2, 2) + 2\alpha_3 J_2(3, 2, 3) + 2\alpha_3 J_1(3, 3) \\
&\quad + 2\alpha_4 J_1(3, 2) + 4\alpha_4 J_1(2, 2), \\
\alpha_2 &= \lambda_2 + 12\alpha_4 J_2(2, 2, 2) + 8\alpha_3 J_1(2, 3), \\
\alpha_3 &= \lambda_3 + 12\alpha_4 J_3(3, 3, 2), \\
\alpha_4 &= \lambda_4 + 4\alpha_4 J_3(2, 2, 2) + 4\alpha_1 J_3(2, 2, 3),
\end{align*}
\]

Finally, we have the function like

\[ \alpha_i(s) = F_i(s, \lambda_i)/D(s), \]
where the masses of these discussed systems can be determined by zeros of \( D(s) \) determinants. And, \( F_i(s, \lambda_i) \) denotes the function of \( s \) and \( \lambda_i \), which determines the contribution of subamplitude.

\[
\begin{align*}
\Theta^+_s(\bar{u}uud\bar{c})/\Theta^-_s(\bar{d}d\bar{d}\bar{d}c) &= 3323 \quad 3323 \quad 3339 \\
\Theta^+_s(\bar{u}uud\bar{c})/\Theta^+_s(\bar{d}d\bar{d}\bar{d}c) &= 2986 \quad 3209 \quad 3277 \\
\Theta^+_s(\bar{d}d\bar{d}\bar{d}c) &= 2980 \quad 3387 \quad 3280
\end{align*}
\]

TABLE I: The obtained low-lying charmed pentaquark masses. Here, the parameters involved in our model include: quark mass \( m_{ud,d} = 439 \) MeV, \( m_c = 1640 \) MeV; cutoff parameter \( \Lambda = 10 \); and gluon coupling constant \( g = 0.825 \). Here, – denotes that there does not exist the corresponding charmed pentaquark state.

In this work, we studied the charmed pentaquarks with \( J^P = 1/2^+, 3/2^+ \) by the relativistic five-quark model, where the Faddeev-Yakubovsky type approach is adopted. The masses of the low-lying charmed pentaquarks are calculated. This information is useful to further experimental search for them in future.

We also notice that there were several experimental efforts on the search for the charmed pentaquarks [24,25], where the present experiment still did not find the evidence of charmed pentaquark. Unlike the mesons, all half-integral spin and parity quantum numbers are allowed in the baryon sector, which means that there exists the mixing between charmed pentaquark and conventional charmed baryon, so that experimentally searching for such charmed pentaquark is not a simple task. In addition, the charmed pentaquarks have the abnormally small widths since the observed charmed pentaquarks with the isospin \( I = 0, 1, 2 \) and the spin-parity \( J^P = 1/2^+, 3/2^+ \) are below the thresholds. These facts make the identification of a pentaquark be difficult in experiment.

In summary, exploring the charmed pentaquark is a reach field full of challenges and opportunities. More theoretical and experimental united efforts should be made in the future to establish charmed exotic pentaquark family.

### Acknowledgments

This work was carried with the support of the RFBR, Research Project (Grant No. 13-02-91154). This project is also supported by the National Natural Science Foundation of China under Grants No. 11222547, No. 11175073, No. 11035006 and No. 11311120054, the Ministry of Education of China (SRFDP under Grant No. 20120211110000), the Fok Ying Tung Education Foundation (Grant No. 131006).

As an interesting research reach topic, exploring the exotic multiquark matter beyond conventional meson and baryon is an exciting and important task, which will be helpful to understand the non-perturbative behavior of quantum chromodynamics. The new observation of numerous XYZ particles opens the Pandora’s Box of studying the exotic multiquark matter [2].
Appendix: Some useful formulae

The definitions of $J_1(l)$, $J_2(l, p)$, and $J_3(l, p)$ are given by

$$J_1(l) = \frac{G_l(s_{12})}{[1 - B_l(s_{12})]} \int_{(m_1 + m_2)^2}^{\infty} ds'_{12} G_l'(s_{12}') \rho_l(s_{12}') \int_{-1}^{+1} dz_1 \frac{dz_1}{2},$$

(16)

$J_2(l, p)$

$$= \frac{G_l(s_{12})G_p(s_{34})}{[1 - B_l(s_{12})][1 - B_p(s_{34})]} \int_{(m_1 + m_2)^2}^{\infty} ds'_{12} \frac{ds'_{34}}{\pi} G_l'(s_{12}') \rho_l(s_{12}') G_p(s_{34}');$$

$$\times \int_{-1}^{+1} dz_3 \int_{-1}^{+1} dz_4 \frac{dz_3}{2} \frac{dz_4}{2},$$

(17)

$J_3(l)$

$$= \frac{G_l(s_{12}, \Lambda)}{1 - B_l(s_{12}, \Lambda)} \frac{1}{4\pi} \int_{(m_1 + m_2)^2}^{\infty} ds'_{12} \frac{ds'_{34}}{\pi} G_l'(s_{12}', \Lambda) \rho_l(s_{12}') G_p(s_{34}');$$

$$\times \int_{-1}^{+1} dz_1 \int_{-1}^{+1} dz_2 \frac{dz_1}{2} \frac{dz_2}{1} \frac{1}{\sqrt{1 - z_1^2 - z_2^2 - z_3^2 + 2z_1z_2}},$$

(18)

respectively, where $l$, $p$ are taken as 1, 2, 3. And $m_i$ denotes the corresponding quark mass. In Eqs. (16) and (18), $z_1$ is the cosine of the angle between the relative momentum of the particles 1 and 2 in the intermediate state and the momentum of the particle 3 in the final state, taken in the c.m. of particles 1 and 2. In Eq. (18), we can define $z$ as the cosine of the angle between the momenta of the particles 3 and 4 in the final state, taken in the c.m. of particles 1 and 2. $z_2$ is the cosine of the angle between the relative momentum of particles 1 and 2 in the intermediate state and the momentum of the particle 4 in the final state, is taken in the c.m. of particles 1 and 2. In Eq. (17), $z_3$ is the cosine of the angle between relative momentum of particles 1 and 2 in the intermediate state and the relative momentum of particles 3 and 4 in the intermediate state, taken in the c.m. of particles 1 and 2. $z_4$ is the cosine of the angle between the relative momentum of the particles 3 and 4 in the intermediate state and that of the momentum of the particle 1 in the intermediate state, taken in the c.m. of particles 3 and 4.

In Eqs. (16)-(17), $G_{\alpha}(s_{ik})$ denote the quark-quark and quark-antiquark vertex functions, where the concrete expressions of $G_{\alpha}(s_{ik})$ are listed in Table III.

In Eq. (17), $B_p(s_{ik})$ is the Chew-Mandelstam function, where $\Lambda_n$ is the cutoff [17]. Additionally, we also list the expressions of vertex function $G_{\alpha}(s_{ik})$.

| $J^{PC}$  | $\alpha(J^{PC},n)$ | $\beta(J^{PC},n)$ | $\gamma(J^{PC})$ |
|----------|-------------------|------------------|------------------|
| $0^+(n = 1)$ | $4g/3 - 2g(m_i + m_k)^2/(3s_{ik})$ | - | - |
| $1^+(n = 2)$ | $2g/3$ | - | - |
| $0^{++}(n = 3)$ | $8g/3$ | - | - |
| $0^{-}(n = 4)$ | $8g/3 - 4g(m_i + m_k)^2/(3s_{ik})$ | - | - |

TABLE II: The expressions of vertex function $G_{\alpha}(s_{ik})$.

In addition, we also list the definitions of some functions used in this work, i.e.,

$$J_1(l, p) = \frac{G_l^2(s_{12}^2)B_p(s_{12}^3)}{B_l(s_{12}^3)} \int_{(m_1 + m_2)^2}^{\infty} ds'_{12} \frac{\rho_l(s_{12}')}{\pi} \frac{dz_1}{2} \frac{1}{1 - B_p(s_{12}')},$$

(20)
\[ J_2(l, p, r) = \frac{G_1'(s_0^2)G_3'(s_0^4)B_2(s_0^{13})}{B_2(s_0^{12})B_3(s_0^{14})} \times \int_{(m_1+m_2)^2}^{\Lambda^2} \frac{ds_0^{12} \rho_0(s_0^{12})}{\pi s_0^{12} - s_0^{15}} \times \int_{(m_1+m_2)^2}^{\Lambda^2} \frac{dz_3}{\pi s_0^{12} - s_0^{15}} \int_{-1}^{1} \frac{dz_3}{2} \\
\times \int_{-1}^{1} dz_4 \frac{1}{2 - B_3(s_0^{14})}. \]

\[ J_3(l, p, r) = \frac{G_1'(s_0^2, \tilde{\Lambda})B_3(s_0^{13})B_2(s_0^{12})}{1 - B_2(s_0^{12})} \times \frac{1}{4\pi} \int_{(m_1+m_2)^2}^{\Lambda^2} \frac{ds_0^{12} \rho_0(s_0^{12})}{\pi s_0^{12} - s_0^{15}} \int_{-1}^{1} \frac{dz_3}{2} \\
\times \int_{-1}^{1} dz \int_{z_1}^{z_2} dz_2 \frac{1}{\sqrt{1 - z^2 - z_1^2 - z_2^2 + 2z_1z_2}} \times \frac{1}{[1 - B_3(s_0^{13})][1 - B_3(s_0^{14})]}. \]

Since other choices of point \( s_0 \) do not change essentially the contributions of \( \alpha_1, \alpha_2, \alpha_3 \) and \( \alpha_4 \), the indexes \( s_0^i \) are omitted here. Due to the weak dependence of the vertex functions on the energy, we treat them as constants in our calculation, which is an approximation. The details of the integration contours of the functions \( J_1, J_2, J_3 \) can be found in Ref. [27].

[1] W. Chen, W.-Z. Deng, J. He, N. Li, X. Liu, Z.-G. Luo, Z.-F. Sun and S.-L. Zhu, arXiv:1311.3763 [hep-ph].
[2] X. Liu, Chin. Sci. Bull. 59, 3815 (2014) arXiv:1312.7408 [hep-ph].
[3] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 110, 252001 (2013) arXiv:1303.5949 [hep-ex].
[4] Z.-F. Sun, J. He, X. Liu, Z.-G. Luo and S.-L. Zhu, Phys. Rev. D 84, 054002 (2011) arXiv:1106.2968 [hep-ph].
[5] Z.-F. Sun, Z.-G. Luo, J. He, X. Liu and S.-L. Zhu, Chin. Phys. C 36, 194 (2012).
[6] T. Nakano et al. [LEPS Collaboration], Phys. Rev. Lett. 91, 012002 (2003) [hep-ex/0301020].
[7] K. H. Hicks, Prog. Part. Nucl. Phys. 55, 647 (2005) [hep-ex/0504027].
[8] C. Amsler et al. [Particle Data Group Collaboration], Phys. Lett. B 667, 1 (2008).
[9] T. Liu, Y. Mao and B.-Q. Ma, arXiv:1403.4455 [hep-ex].
[10] S. M. Gerasyuta and V. I. Kochkin, Phys. Rev. D 66, 116001 (2002) [hep-ph/0203104].
[11] G. ’t Hooft, Nucl. Phys. B 72, 461 (1974).
[12] G. Veneziano, Nucl. Phys. B 117, 519 (1976).
[13] E. Witten, Nucl. Phys. B 160, 57 (1979).
[14] O. A. Yakubovsky, Sov. J. Nucl. Phys. 5, 937 (1967) [Yad. Fiz. 5, 1312 (1967)].
[15] S.P. Merkuriev and L.D. Faddeev. Quantum Scattering Theory for System of Few Particles. (Nauka, Moscow, 1985) p. 398.
[16] V. V. Anisovich, S. M. Gerasyuta and A. V. Sarantsev, Int. J. Mod. Phys. A 6, 625 (1991).
[17] G. F. Chew and S. Mandelstam, Phys. Rev. 119, 467 (1960).
[18] S. M. Gerasyuta and V. I. Kochkin, Phys. Atom. Nucl. 61, 1398 (1998) [Yad. Fiz. 61, 1504 (1998)].
[19] V.V. Anisovich and A.A. Anselm, Usp. Phys. Nauk 88, 287 (1966).
[20] S. M. Gerasyuta and V. I. Kochkin, Phys. Rev. D 78, 116004 (2008) [arXiv:0804.4567 [hep-ph]].
[21] S. M. Gerasyuta and V. I. Kochkin, Phys. Rev. D 72, 016002 (2005) [hep-ph/0504254].
[22] R. Chen, Z.-F. Sun, X. Liu and S. M. Gerasyuta, arXiv:1406.7481 [hep-ph].
[23] M. Harada and Y. L. Ma, Phys. Rev. D 87, no. 5, 056007 (2013) [arXiv:1212.3079 [hep-ph]].
[24] B. Aubert et al. [BaBar Collaboration], Phys. Rev. D 73, 091101 (2006) [hep-ex/0604006].
[25] G. De Leo, A. V. Guler, J. Kawada, U. Kose, O. Sato and F. Tramontano, Nucl. Phys. B 763, 268 (2007).
[26] U. Karshon [H1 and ZEUS Collaboration], arXiv:0907.4574 [hep-ex].
[27] S. M. Gerasyuta and V. I. Kochkin, Phys. Rev. D 71, 076009 (2005) [hep-ph/0310227].