Closed-flavor $\pi J/\psi$ and $\pi \Upsilon$ Cross Sections at Low Energies from Dipion Decays

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The scale of low energy $c\bar{c}$ and $b\bar{b}$ cross sections on light hadrons is of great importance to searches for the quark gluon plasma using the heavy-quarkonium suppression signature. Unfortunately, little is known about these near-threshold cross sections at present, and recent theoretical estimates span many orders of magnitude. Here we use experimental data on the four observed closed-flavor heavy quarkonium hadronic decays $\psi' \to \pi \pi J/\psi$, $\Upsilon' \to \pi \pi \Upsilon$, $\Upsilon'' \to \pi \pi \Upsilon$ and $\Upsilon'' \to \pi \pi \Upsilon'$, combined with simple models of the transition amplitudes, to estimate the pion scattering cross sections of $c\bar{c}$ and $b\bar{b}$ mesons near threshold. Specifically we consider the closed-flavor reactions $\pi J/\psi \to \pi \psi'$, $\pi \Upsilon \to \pi \Upsilon'$, $\pi \Upsilon \to \pi \Upsilon''$ and $\pi \Upsilon' \to \pi \Upsilon''$ and their time-reversed analogues. Our results may be useful in constraining theoretical models of the strong interactions of heavy quarkonia, and can be systematically improved through future detailed studies of dipion decays, notably $\psi' \to \pi \pi J/\psi$ and $\Upsilon' \to \pi \pi \Upsilon$.

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INTRODUCTION

One signature proposed for the identification of a quark-gluon plasma (QGP) is a suppressed rate of formation of charmonium bound states, due to the screening effect of the plasma on the linear confining potential that normally binds a $c\bar{c}$ pair \cite{1}. In the presence of this screening, $c\bar{c}$ pairs produced within the plasma presumably separate into open charm mesons, so that the formation of a QGP would be signaled by a decrease in the charmonium production cross section.

This attractively simple picture becomes more complicated if the dissociation cross sections of charmonia on light hadrons are not small. In this case the charmonia produced during a heavy-ion collision may rescatter into open-charm final states as the result of interactions with the “comoving” light hadrons produced in the collision.

Due to the importance of these cross sections for QGP searches, many calculations of near-threshold scattering cross sections of light hadrons on charmonia have recently been reported. The methods applied include a high energy color-dipole scattering model \cite{2}, quark models \cite{3,4,5}, meson exchange models \cite{6,7,8}, and most recently QCD sum rules \cite{9,10}.

Under certain simplifying assumptions one may relate experimentally known hadron decays to heavy quarkonium scattering cross sections. Here we consider the dipion decays of heavy quarkonia below open-flavor thresholds, which have been observed in four cases, $\psi' \to \pi \pi J/\psi$ \cite{11,12,13}, $\Upsilon' \to \pi \pi \Upsilon$ \cite{14,15,16,17,18,19}, $\Upsilon'' \to \pi \pi \Upsilon$ \cite{15,16,17,18,19} and $\Upsilon'' \to \pi \pi \Upsilon$ \cite{15,16,17,18,19}. These transitions are quite weak, with partial widths of only ca. 100 keV for $c\bar{c}$ and 1–10 keV for $b\bar{b}$. They have been observed only because the total widths of the initial heavy quarkonia, which lie below their open-flavor thresholds, are also very small.

We can use these three-body partial widths to estimate pion scattering cross sections of the corresponding heavy quarkonia, since these processes are described by the same invariant amplitudes. The pion scattering cross sections are given by

$$\sigma_{\pi_1 M_a \to \pi_2 M_b} = \frac{1}{64\pi s} \frac{1}{p_f^2} \int_{t_1}^{t_2} dt \langle |A|^2 \rangle$$

where as usual $s = m^2_{\pi_1 M_a} = m^2_{\pi_2 M_b}$, $t = (p_{\pi_1} - p_{\pi_2})^2$, the limits are $t_1 = -2|E_{\pi_1} - E_{\pi_2} + \vec{p}_f|$, and frame-dependent quantities such as $E_{\pi_1}$ and $p_i = |\vec{p}_i|$ are understood to be evaluated in the c.m. frame.

The corresponding dipion three-body partial width is

$$\Gamma_{M_b \to \pi_1 \pi_2 M_a} = \frac{1}{(2\pi)^3} \frac{1}{32M_b^2} \int ds dt \langle |A|^2 \rangle$$
where $s$ and $t$ (after crossing) become $s = M_{\pi\pi}^2$ and $t = M_{\pi\pi}^2 - m_{\pi}^2$. Our Eqs.(1,2) correspond to Eqs.(37,30,21) of the 2002 PDG [20].

Our convention is that $M_b$ is higher in mass than $M_a$, so the dipion decay $M_b \rightarrow \pi\pi M_a$ is energetically allowed but $M_a \rightarrow \pi\pi M_b$ is not. The initial and final mesons in the cross section formula Eq.(1) may be $(M_b, M_a)$ as shown, or they may be transposed to $(M_a, M_b)$, since the same invariant amplitude $A$ is involved. As an example, the decay $\psi' \rightarrow \pi^+\pi^- J/\psi$ is related to both $\pi^+ J/\psi \rightarrow \pi^+\pi' J/\psi$ and $\pi^+\pi' J/\psi \rightarrow \pi^+ J/\psi$.

Since the squared invariant amplitude $\langle |A|^2 \rangle$ is sampled in different kinematic regions by the decay and the cross sections (see Fig.1), assumptions regarding the form of $\langle |A|^2 \rangle$ are required to relate these various processes. In the following we shall obtain results for the cross sections given three simple models of the invariant amplitudes.

**CONSTANT $A$ APPROXIMATION**

As a first approximation we neglect any dependence of $\langle |A|^2 \rangle$ on kinematics, and simply treat it as a constant. In this case Eqs.(1,2) imply a simple relation between the pion cross section and the dipion partial decay width,

$$\sigma_{\pi M_a \rightarrow \pi M_b} = \Gamma_{M_b \rightarrow \pi \pi M_a} \cdot \frac{16\pi^2 M_b^3}{A_D} \frac{p_f}{p_i} \frac{1}{s-1} \equiv c_0 \frac{p_f}{p_i} \frac{1}{s-1}$$

where $A_D$ is the area of the $M_b \rightarrow \pi\pi M_a$ dipion decay Dalitz plot

$$A_D = \int \int dm_{\pi M_a}^2 dm_{\pi M_a}^2 = \int ds \int dt$$

and $p_i = p_a$ and $p_f = p_b$ are the three-momenta of the initial and final pions (or heavy mesons) in the reaction $\pi M_a \rightarrow \pi M_b$ in the c.m. frame. The Dalitz plot for the decay $\psi' \rightarrow \pi^+\pi^- J/\psi$ and the related reactions $\pi^+ J/\psi \rightarrow \pi^+\psi'$ and $\pi^+\psi' \rightarrow \pi^+ J/\psi$ are shown as examples in Fig.1. The Dalitz plot areas $\{A_D\}$ and dipion widths used in this work are given in Table 1; the masses assumed are $m_{\pi^+} = 0.1396$ GeV, $M_{J/\psi} = 3.097$ GeV, $M_{\psi'} = 3.686$ GeV, $M_T = 9.460$ GeV, $M_{Y'} = 10.023$ GeV and $M_{Y''} = 10.355$ GeV.

The cross sections for the reactions $\pi^+ J/\psi \rightarrow \pi^+\psi'$ and $\pi^+\psi' \rightarrow \pi^+ J/\psi$ in the constant amplitude approximation are shown in Fig.2. Evidently the scales of these cross sections a few hundred MeV above threshold are ca. 20 $\mu$b for the endothermic process $\pi^+ J/\psi \rightarrow \pi^+\psi'$ and ca. 0.1 $\mu$b for its crossed exothermic partner $\pi^+\psi' \rightarrow \pi^+ J/\psi$. This method applied to pion cross sections in the upsilon family yields cross sections of ca. 2 $\mu$b for $\pi^+ Y \rightarrow \pi^+ Y'$ and ca. 10 $\mu$b for $\pi^+ Y' \rightarrow \pi^+ Y$ in the

![FIG. 1: Dalitz plot of kinematically allowed regions for the decay $\psi' \rightarrow \pi^+\pi^- J/\psi$ and the reactions $\pi^+ J/\psi \rightarrow \pi^+\psi'$ and $\pi^+\psi' \rightarrow \pi^+ J/\psi$.](image)

![FIG. 2: $\sigma_{\pi^+ J/\psi \rightarrow \pi^+\psi'}$ (lower) and $\sigma_{\pi^+\psi' \rightarrow \pi^+ J/\psi}$ (upper) estimated from $\Gamma_{\psi' \rightarrow \pi^+\pi^- J/\psi}$ assuming constant amplitudes.](image)

![FIG. 3: $\sigma_{\pi^+ Y \rightarrow \pi^+ Y'}$ (lower) and $\sigma_{\pi^+ Y' \rightarrow \pi^+ Y}$ (upper) estimated from $\Gamma_{Y' \rightarrow \pi^+\pi^- Y}$ assuming constant amplitudes.](image)
The first two categories are gluon radiation models \cite{21,22,23}, 2) scalar anomaly models \cite{12}. The first two categories predict rather similar \( m_{\pi\pi} \) dependences, so we will consider them together. There is also a suggestion that chiral symmetry, combined with certain simplifying assumptions for amplitudes, can explain the observed \( m_{\pi\pi} \) dependence in \( \psi' \rightarrow \pi^+\pi^-J/\psi \) \cite{31}; this model suggests an \( m_{\pi\pi} \) dependence similar to the first two categories. Finally, we note that several references have considered the decay \( \Upsilon'' \rightarrow \pi\pi\Upsilon \) as a special case, since it has a “double-humped” dipion distribution that is not seen in other decays \cite{31,32}.

Gluon radiation and scalar anomaly models assume that the important low-energy \( m_{\pi\pi} \) dependence is determined by aspects of a purely gluonic intermediate state. In gluon radiation models this strong energy dependence arises from a multipole expansion of the gluon emission amplitude, whereas in the scalar anomaly models it is the momentum dependence encountered in coupling the gluonic state to the \( \pi\pi \) final state. Clearly it will be difficult to distinguish these two possibilities, although a detailed comparison of their predictions with experiment appears to favor the scalar anomaly model \cite{12}.

In the scalar anomaly model one can relate the \( \pi\pi \) production amplitude to the matrix element of the simplest scalar gluon operator between the vacuum and a \( \pi\pi \) state, \( \langle \pi\pi|G_{\mu\nu}^aG_{\mu\nu}^a|0 \rangle \). This matrix element can be determined because the operator \( G_{\mu\nu}^aG_{\mu\nu}^a \) is proportional to the triangle anomaly in the trace of the energy-momentum tensor, which in a low energy pion effective lagrangian is quadratic in the pion field. The matrix element of this operator gives a near-threshold dependence of \( A \propto m_{\pi\pi}^2 \), which is \( A \propto t \) in our kinematics.

Meson exchange models assume that the \( \pi\pi \) system is produced by an intermediate scalar \( f_0 \) meson (often referred to as the “\( \sigma \)”), and the observed \( m_{\pi\pi} \) dependence at higher invariant mass is due primarily to this meson. Fits to the dipion data (excluding the problematic \( \Upsilon'' \rightarrow \pi\pi\Upsilon \)) typically prefer a light, broad state with a mass near 0.5 GeV; see for example \cite{28,24,32}.

Ideally we would cross an accurate model of the \( \pi\pi \) production amplitudes into the \( \pi \) scattering regime to estimate \( \pi+(Q\bar{Q}) \) closed-flavor cross sections, but this is not yet possible because no model gives a good simultaneous description of all the experimentally observed \( c\bar{c} \) and \( b\bar{b} \) dipion mass distributions. For the present we will simply assume the near-threshold \( m_{\pi\pi} \) dependences suggested by the existing models, and evaluate the cross sections predicted for \( \pi^+J/\psi \rightarrow \pi^+\psi' \) in each case.

For the gluon radiation and scalar anomaly models we assume

\[
|\langle A(s,t) \rangle|^2 = c_{\pi}t^n. \tag{5}
\]

For a power-law form \( |\langle A(s,t) \rangle|^2 = c_{\pi}t^n \), the relation between decays and cross sections Eq.(3) generalizes as follows; the decay rate Eq.(2) becomes

\[
\Gamma_{M_b \rightarrow \pi\pi M_a} = \frac{1}{256\pi^3 M_b^3} c_n I^{(n)} \tag{6}
\]

where \( I^{(n)} \) is the integral of \( t^n \) over the \( M_b \rightarrow \pi\pi M_a \) Dalitz plot,

\[
I^{(n)} = \int ds \, dt \, t^n. \tag{7}
\]

The constant \( c_n \) is determined by the measured dipion partial width using Eq.(6), and substitution of \( c_n t^n \) into the cross section formula Eq.(1) then gives

\[
\sigma_{\pi M_a \rightarrow M_b} = \frac{4\pi^2 M_b^3}{(n+1) I^{(n)}} \frac{1}{s p_{t}} \left( |t_1|^{n+1} - |t_2|^{n+1} \right). \tag{8}
\]

### Table 1: Experimental dipion-decay Dalitz plot areas, transition rates and cross section coefficients.

| Decay                  | \( A_0 \) [GeV\(^4\)] | \( \Gamma_{\pi^+\pi^-} \) [keV] | \( c_{\pi} \) [mb GeV\(^2\)] |
|------------------------|------------------------|-------------------------------|-------------------------------|
| \( \psi' \rightarrow \pi^+\pi^-J/\psi \) | 0.436 | 91.5 ± 9.0 | 0.65 ± 0.06 |
| \( \Upsilon' \rightarrow \pi^+\pi^-\Upsilon \) | 1.023 | 8.3 ± 1.3 | 0.50 ± 0.08 |
| \( \Upsilon'' \rightarrow \pi^+\pi^-\Upsilon \) | 6.679 | 1.2 ± 0.2 | 0.012 ± 0.001 |
| \( \Upsilon'' \rightarrow \pi^+\pi^-\Upsilon' \) | 0.027 | 0.7 ± 0.2 | 1.9 ± 0.5 |

The analogous kinematic regime (Fig.3).
We again specialize to the process $\pi^+ J/\psi \rightarrow \pi^+ \psi'$. Setting $n = 2$ (scalar anomaly models), for Eq.(7) we find $\Gamma^{(2)} = 0.01954$ GeV$^8$. The cross section in Eq.(8) may then be evaluated numerically, which gives the result shown in Fig.5. Note that the scalar anomaly model leads to a rapid increase of the cross section relative to the constant amplitude model above $\sqrt{s} \approx 3.9$ GeV. This is due to the $t^2$-weighting combined with the rapid increase in the range of $t$ covered by this reaction with increasing $\sqrt{s}$, which is evident in Fig.1 (lower right region).

Finally, for our meson exchange model we assume a generalized Breit-Wigner form which incorporates the scalar anomaly soft-pion factor. For $t > 0$ this is

$$\langle |A(s,t)|^2 \rangle = \left( \frac{t^2}{\sqrt{t^2 - M_{f_0}^2} + \Gamma_{f_0}^2 / 4} \right)^2$$

(9)

where $M_{f_0}$ and $\Gamma_{f_0}$ are the mass and width of the hypothetical scalar meson source of the $\pi\pi$ events. We have incorporated the $t^2$ scalar anomaly soft-pion dependence in Eq.(9) because pure Breit-Wigner forms required an unrealistically narrow $f_0$ ($\Gamma_{f_0} \approx 100$-150 MeV) and gave rather poor fits to the data. In contrast the hybrid form Eq.(9) clearly gives an acceptable fit (Fig.4), although we emphasize that this meson exchange model is unphysical because the fitted parameters $M_{f_0} = 536$ MeV and $\Gamma_{f_0} = 260$ MeV are inconsistent with the experimental $I=0 \pi\pi$ S-wave phase shift.

We can again use Eqs.(1,2) to determine the cross section for $\pi^+ J/\psi \rightarrow \pi^+ \psi'$ implied by this decay model (ignoring the problem of disagreement with phase shifts). The result is

$$\sigma_{\pi \mathcal{M}_b \rightarrow \pi \mathcal{M}_b} =$$

$$\Gamma_{\mathcal{M}_b \rightarrow \pi \mathcal{M}_b} \cdot \frac{4\pi^2 M_b^3}{I_{f_0}} \cdot \frac{1}{s\rho_{f_0}} \int_{t_1}^{t_2} \frac{t^2 dt}{\sqrt{t^2 - M_{f_0}^2} + \Gamma_{f_0}^2 / 4}.$$  

(10)

Note that this integration is over negative values of $t$, whereas the decay rate integral is over positive $t$, which leads to different signs in the Breit-Wigner functions. The Dalitz plot decay integral

$$I_{f_0} \equiv \int ds dt \frac{t^2}{\sqrt{t^2 - M_{f_0}^2} + \Gamma_{f_0}^2 / 4}.$$ 

(11)

for $\psi' \rightarrow \pi^+\pi^- J/\psi$ equals 0.08069 GeV$^6$ given our external meson masses and fitted $f_0$ parameters. The integral over $t$ in Eq.(10) is

$$I = M_{f_0} \left( \frac{1}{2} t^4 - \frac{10}{3} t^3 + (10 - c^2) t^2 - (20 - 10 c^2) t \right. \right.$$

$$\left. \left. + (5 - 10 c^2 + c^4) \ln(t^2 + c^2) \right) \right.$$ 

(12)

where $c = \Gamma_{f_0} / 2 M_{f_0}$. Combining Eqs.(10-12) gives the meson exchange model prediction for $\sigma_{\pi^+ J/\psi \rightarrow \pi^+ \psi'}$, which is also shown in Fig.5. Evidently the meson exchange cross section is suppressed near threshold, due to the separation from the $f_0$ pole.

**COMPARISON WITH PREVIOUS WORK**

Two of the theoretical references on dipion decays cited previously, Sorge, Shuryak and Zahed [27] and Chen and Savage [28], also discussed results for closed-flavor pion scattering cross sections with heavy quarkonia, specifi-
cally for $\pi^+ J/\psi \rightarrow \pi^+ \psi'$ at low energies. Since these references actually used dipion decay data to normalize their scattering amplitudes, approximate agreement with our results should be anticipated. Fujii and Kharzeev have also evaluated closed-flavor charmonium cross sections, using a color-dipole scattering model. They do not use dipion decay data as a direct input, although they do note that their two results for the rate $\Gamma(\psi' \rightarrow \pi \pi J/\psi)$ are not far from experiment.

In the earliest reference, Sorge et al. assume scalar meson exchange with a high-mass $f_0(1400)$ as the $\pi\pi$ source. (They make the important and often neglected observation that assuming a low-mass $f_0$ of only moderate width, as in Fig.4, disagrees with the experimental $I=0$ $\pi\pi$ S-wave phase shift.) Their cross section close to threshold is shown in Fig.6, and is evidently qualitatively similar to our scalar anomaly model result. Chen and Savage used a gluon radiation model to describe this reaction, and quoted cross sections at tree level and with one-loop chiral corrections. These results are also shown in Fig.6, and are numerically rather similar to Sorge et al. Finally, Fujii and Kharzeev used a color-dipole scattering model, and quote results for the $\pi\pi$ system. (Their form factor is inferred from the $I=0$ $\pi\pi$ S-wave phase shift.) Their results without a form factor are similar to the earlier predictions. With a form factor they find a much smaller cross section, which is rather close to our scalar meson exchange result.

**SUMMARY AND CONCLUSIONS**

The search for the quark gluon plasma has led to great interest in the scale of the cross sections of heavy quarkonia interacting with light hadrons near threshold. Unfortunately, little is known about these cross sections experimentally. In this paper we have used crossing symmetry and several simple amplitude models to estimate the closed-flavor cross sections for heavy quarkonia scattering on pions near threshold, using the experimentally known dipion decays as input. The method is applied both to charmonia and to the $b\bar{b}$ system. For the simplest cases of $1S \leftrightarrow 2S$ transitions, assuming constant amplitudes we estimate the cross sections a few hundred MeV above threshold to be ca. 20 $\mu$b for $\pi J/\psi \rightarrow \pi \psi'$, and ca. 2 $\mu$b for $\pi \Upsilon \rightarrow \pi \Upsilon'$. The corresponding time-reversed, exothermic reactions are estimated to be about 0.1 mb and 10 $\mu$b respectively.

We note that the strong dependence of the decay amplitude on $t = m^2_{\pi\pi}$ observed experimentally in the dipion decays near threshold makes analytic continuation to the pion scattering regime rather problematic. The dependence of the cross section for $\pi J/\psi \rightarrow \pi \psi'$ (used as our example) on the different model amplitudes is clearly evident even near threshold (Fig.5). For this reaction the various models we considered gave consistent cross sections of $\sim 5-15$ $\mu$b at $E_{cm} = 3.9$ GeV, but the predictions diverged rapidly with increasing invariant mass.

In future, high statistics studies of dipion decays at CLEO might provide additional useful information about the decay amplitude. In particular, it would be useful to accurately determine the $s$ dependence of the decay amplitude in the Dalitz plot of Fig.1 experimentally, in addition to the already well known $t = m^2_{\pi\pi}$ dependence.

We note in passing that the cross sections for these near-threshold closed-flavor processes are much smaller than the millibarn scale typically found for open-flavor reactions such as $\pi J/\psi \rightarrow D^* D$. The possibility that the rather weak closed-flavor reactions are due to open-flavor scattering at second order is intriguing, rather than to exchange of an unphysically light scalar meson, is an interesting suggestion which merits future investigation.

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[1] T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986).
[2] D. Kharzeev and H. Satz, Phys. Lett. B 334, 155 (1994) [arXiv:hep-ph/9405414].
[3] K. Martins, D. Blaschke and E. Quack, Phys. Rev. C 51, 2723 (1995) [arXiv:hep-ph/9411302].
[4] C. Y. Wong, E. S. Swanson and T. Barnes, Phys. Rev. C 62, 045201 (2000) [arXiv:hep-ph/9912431].
[5] T. Barnes, E. S. Swanson, C. Y. Wong and X. M. Xu, arXiv:nucl-th/0302052.
[6] S. G. Matinian and B. M"uller, Phys. Rev. C 58, 2994 (1998) [arXiv:nucl-th/9806027].
[7] K. L. Higgin, Phys. Rev. C 61, 031902 (2000) [arXiv:nucl-th/9907034].
[8] F. S. Navarra, M. Nielsen and M. R. Robilotta, Phys. Rev. C 64, 021901 (2001) [arXiv:nucl-th/0103051].
[9] F. S. Navarra, M. Nielsen, R. S. Marques de Carvalho and G. Krein, Phys. Lett. B 529, 87 (2002) [arXiv:nucl-th/0105058].
[10] P. O. Duras, H. c. Kim, S. H. Lee, F. S. Navarra and M. Nielsen, arXiv:nucl-th/0211092.
[11] T. A. Armstrong et al. [Fermilab E760 Collaboration], Phys. Rev. D 55, 1153 (1997).
[12] J. Z. Bai et al. [BES Collaboration], Phys. Rev. D 62 (2000) 032001 [arXiv:hep-ex/9909038].
[13] M. Ambrogiani et al. [ES85 Collaboration], Phys. Rev. D 62, 032004 (2000).
[14] D. Besson et al. [CLEO Collaboration], Phys. Rev. D 30, 1433 (1984).
[15] T. J. Boscok et al. [CLEO Collaboration], Phys. Rev. Lett. 58, 307 (1987).
[16] I. C. Brock et al., Phys. Rev. D 43, 1448 (1991).
[17] F. Butler et al. [CLEO Collaboration], Phys. Rev. D 49, 40 (1994).
[18] U. Heintz et al., Phys. Rev. D 46 (1992) 1928.
[19] Q. W. Wu et al., Phys. Lett. B 301 (1993) 307.
[20] K. Hagiwara et al. [Particle Data Group Collaboration], Phys. Rev. D 66, 010001 (2002).
[21] K. Gottfried, Phys. Rev. Lett. 40, 598 (1978).
[22] T. M. Yan, Phys. Rev. D 22, 1652 (1980).
[23] J. W. Chen and M. J. Savage, Phys. Rev. D 57, 2837 (1998) [arXiv:hep-ph/9710338].
[24] M. B. Voloshin, JETP Lett. 21, 347 (1975) [Pisma Zh. Eksp. Teor. Fiz. 21, 733 (1975)].
[25] M. B. Voloshin and V. I. Zakharov, Phys. Rev. Lett. 45 (1980) 688.
[26] V. A. Novikov and M. A. Shifman, Z. Phys. C 8, 43 (1981).
[27] H. Sorge, E. V. Shuryak and I. Zahed, Phys. Rev. Lett. 79, 2775 (1997) [arXiv:hep-ph/9705329].
[28] T. Komada, S. Ishida and M. Ishida, arXiv:hep-ph/0012327.
[29] T. A. Lahde and D. O. Riska, Nucl. Phys. A 707, 425 (2002) [arXiv:hep-ph/0112151].
[30] L. S. Brown and K. R. Cahn, Phys. Rev. Lett. 35, 1 (1975).
[31] P. Moxhay, Phys. Rev. D 39, 3497 (1989).
[32] V. V. Kiselev and A. K. Likhoded, arXiv:hep-ph/9406219.
[33] M. Ishida, S. Ishida, T. Komada and S. I. Matsumoto, AIP Conf. Proc. 619, 735 (2002) [arXiv:hep-ph/0110358].
[34] H. Fuji and D. Kharzeev, Phys. Rev. D 60, 114039 (1999) [arXiv:hep-ph/9903495].
[35] H. J. Lipkin and S. F. Tuan, Phys. Lett. B 206, 349 (1988).
[36] H. J. Lipkin and S. F. Tuan, Phys. Rev. Lett. 62, 2910 (1989).