Tetraquarks composed of 4 heavy quarks

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In the current work spectroscopy and possibility of observation at the LHC of tetraquarks composed of 4 heavy quarks is discussed. Tetraquarks concerned are \( T_{4c} = [cc][\bar{c}\bar{c}] \), \( T_{4b} = [bb][\bar{b}\bar{b}] \) and \( T_{2[bc]} = [bc][\bar{b}\bar{c}] \). By solving nonrelativistic Schroedinger equation masses of these states are found with the hyperfine splitting accounted for. It is shown that masses of tensor tetraquarks \( T_{4c}(2^{++}) \) and \( T_{2[bc]}(2^{++}) \) are high enough to observe these states as peaks in the invariant mass distributions of heavy quarkonia pairs in pp → \( T_{4c} \rightarrow X \rightarrow 2J/\psi + X \), pp → \( T_{2[bc]} \rightarrow X \rightarrow 2B_c + X \) and pp → \( T_{4b} \rightarrow X \rightarrow J/\psi Y(1S) + X \) channels while \( T_{4b} \) is under the threshold of decay into a vector bottomonia pair.

I. INTRODUCTION

Recent observation of \( J/\psi \)-meson pairs production in proton-proton collisions at 7 TeV energy at LHC renewed interest to the 4 heavy quarks final states. In the low invariant mass region these quarks can form bound states (called tetraquarks) which can be produced in hadronic experiments. Thereby we would like to discuss physics of these states, elaborate their mass spectrum and possibility of experimental observation.

Conception of tetraquarks, i.e. mesons composed of 4 valent quarks (\( qq\bar{q}\bar{q} \)), was first introduced in works \[1, 2\] in 1976. For example, \( a_0 \)-meson and \( \sigma \)-mesons was treated as possible tetraquark candidate \[3, 6\]. However, it is hard to determine quark composition of a particle in the light meson domain so these ideas were not developed further. Observation of new unexpected states such as \( X(3872) \[7, 8\] \) gave this idea a new impetus \[9, 10\]. Eccentricity of these particles consists in fact that according to the modes of their production and decay they contain a \( c\bar{c} \) pair but they can not be included in the well known systematics of charmonia. Later similar particles were also found in the bottomonia sector \[11–14\]. It is natural to ascribe these mesons to tetraquarks \( (Qq\bar{q}\bar{q}) \), where \( q \) are light and \( Q \) — heavy (\( b \) or \( c \) ) quarks.

However, situation when all quarks composing a tetraquark are heavy was not treated in details yet. This possibility seems to be quite interesting as in this case determination of meson’s quark composition becomes simpler and its parameters can be determined by solving nonrelativistic Schroedinger equation. Our work is devoted to these particular questions.

In our recent paper \[15\] we consider tetraquark \( T_{4c} = [cc][\bar{c}\bar{c}] \) in the framework of diquark model. The hyperfine splitting in that paper was described through interaction of total diquark spins. Now we would like to study also tetraquarks \( T_{4b} = [bb][\bar{b}\bar{b}] \) and \( T_{2[bc]} = [bc][\bar{b}\bar{c}] \). The last state is especially interesting since, in contrast to tetraquarks build from four identical quarks, both singlet and triplet spin states of the diquark are possible. It is clear, that hyperfine interaction of spin-singlet diquark cannot be described with the method used in our previous paper, so some other approach should be applied.

In the following section spectroscopy of \((cc\bar{c}\bar{c}), (bb\bar{b}\bar{b}) \) and \((bc\bar{b}\bar{c})\) tetraquarks is concerned. Possibility of observation of these particles in hadronic experiments is discussed in the third section. We summarize our results in the short conclusion.

II. SPECTROSCOPY

A. General preliminaries

In the current study diquark model of tetraquark is used. According to this approach tetraquark

\[ T = Q_1\bar{Q}_2\bar{Q}_3\bar{Q}_4 \]
consists of 2 almost point-like diquarks $\bar{D}_{12} = [Q_1Q_2]$ and $D_{34} = [\bar{Q}_3\bar{Q}_4]$ with certain quantum numbers (such as angular momentum, spin, color) and mass. What concerns color configuration, two quarks in diquark can be in triplet or sextet color state. According to the manuscript [16] in the sextet configuration diquarks experience mutual repulsion so we restrict ourselves to the (anti)triplet color configurations. Angular momentum of the diquark system equals 0 in the ground state, so its spin is equal to the sum of quark spins which is 0 or 1. What concerns diquark mass, it can be determined by solving Schroedinger equation with a correctly selected potential. According to work [17] it is possible to use quark-antiquark interaction potential used in heavy quarkonia calculations with additional factor 1/2 due to the different color structures.

In the diquark model tetraquark mass can be determined by solving 2-particle Schroedinger equation with point-like diquarks. As $[Q_1Q_2]$ and $[\bar{Q}_3\bar{Q}_4]$ diquarks are in (anti)triplet color configuration, potential of their interaction coincides with that of quark and antiquark in heavy quarkonia. Hyperfine splitting in this system can be described by the hamiltonian [3]

$$ H = M_0 + 2 \sum_{i<j} \kappa_{ij} (S_i S_j), \quad (1) $$

where $M_0$ is the tetraquark mass without splitting, $S_i$ — spin operator of $i$-th (anti)quark, and $\kappa_{ij}$ are constants determined from experimental data analysis or theoretically. When dealing with potential models, $\kappa_{ij}$ coefficient can be obtained from the value of the $Q_i Q_j$ system wave function at origin:

$$ \kappa_{ij} = \frac{1}{2} \frac{4}{m_{Q_i} m_{Q_j}} \alpha_s |R_{ij}(0)|^2 \quad (2) $$

when both $Q_i$ and $Q_j$ are quarks or antiquarks in the color triplet state, and

$$ \kappa_{ij} = \frac{8}{2} \frac{4}{m_{Q_i} m_{Q_j}} \alpha_s |R_{ij}(0)|^2 \quad (3) $$

if $Q_i$ and $Q_j$ are quark and antiquark in color singlet configuration. Three loop expression for the strong coupling constant was used when calculating $\kappa_{ij}$ constants [17] and scale for it was taken equal

$$ \mu^2 = \frac{2 m_{Q_i} m_{Q_j}}{m_{Q_i} + m_{Q_j}} \langle T \rangle $$

where $\langle T \rangle$ is average kinetic energy of quarks which is equal

$$ \langle T_d \rangle = 0.19 \text{ GeV} $$

and

$$ \langle T_s \rangle = 0.38 \text{ GeV} $$

for the triplet and singlet states respectively. Values of diquark wave functions in origin are presented in manuscript [17] while for mesons they can be calculated from the leptonic width $\Gamma_{ee}$ or leptonic constant $f$ of meson in question:

$$ |R(0)|^2 = \frac{1}{\alpha^2 \kappa^2} \frac{M^2}{4} = \frac{M^2 f}{9}. $$

Up to the hyperfine splitting tetraquark can be described by its total spin $J$, spins of diquarks $S_{12}$ and $S_{34}$ constituting it and its spatial and charge parities $P$ and $C$:

$$ |0^{++}\rangle = |0; 0, 0\rangle, \quad |0^{++}'\rangle = |0; 1, 1\rangle, $$

$$ |1^{++}\rangle = \frac{1}{\sqrt{2}} (|1; 0, 1\rangle \pm |1; 0, 1\rangle), \quad |1^{+-}\rangle = |1; 1, 1\rangle, $$

$$ |2^{++}\rangle = |2; 1, 1\rangle $$

In this treatment all states are confluent with mass $M_0$. If spin-spin interaction is accounted for, masses of $|1^{++}\rangle$ and $|2^{++}\rangle$ states shift:

$$ M (1^{++}) = \langle 1^{++} | H | 1^{++} \rangle = M_0 - \kappa_{12} - \kappa_{-}, \quad M (2^{++}) = 2 m_{[12]} + \kappa_{12} + \kappa_{+}, $$
where following designations are introduced:

\[ \kappa_\pm = \frac{2\kappa_{14} \pm \kappa_{13} \pm \kappa_{24}}{2}, \]

doing \(|0^{++}\rangle, |0^{++'}\rangle\) and \(|1^{+-}\rangle, |1^{+-'}\rangle\) states mix with each other. In the scalar tetraquarks case mixing matrix has the following form:

\[
H \begin{bmatrix} |0^{++}\rangle \\ |0^{++'}\rangle \end{bmatrix} = \begin{bmatrix} M_0 - 3\kappa_{12} & -\sqrt{3}\kappa_- \\ -\sqrt{3}\kappa_- & M_0 + \kappa_{12} - 2\kappa_+ \end{bmatrix} \begin{bmatrix} |0^{++}\rangle \\ |0^{++'}\rangle \end{bmatrix},
\]

and for \(|1^{+-}\rangle\) tetraquarks:

\[
H \begin{bmatrix} |1^{+-}\rangle \\ |1^{+-'}\rangle \end{bmatrix} = \begin{bmatrix} M_0 - \kappa_{12} + \kappa_- & \kappa_{13} - \kappa_{24} \\ \kappa_{13} - \kappa_{24} & M_0 + \kappa_{12} - \kappa_+ \end{bmatrix} \begin{bmatrix} |1^{+-}\rangle \\ |1^{+-'}\rangle \end{bmatrix}.
\]

B. \([QQ][QQ]\]

In the case when quarks of the same flavor are involved, Fermi-Dirac statistics leads to the additional restrictions on the diquark quantum numbers. Indeed, permutation of quark indices should change sign of the total diquark wave function. As quarks are in the antitriplet color state, color part of this function is antisymmetric. Radial wave function is symmetric as quarks are in the \(S\)-wave. So spin part of the wave function is to be symmetric too. Consequently the total spin of the \(S\)-wave diquark can only be equal to 1. As a result only \(|0^{++}\rangle, |1^{++}\rangle\) and \(|2^{++}\rangle\) diquark states remain. They do not mix with each other after the spin-spin interaction is accounted for. Masses of these states are equal

\[
M \begin{bmatrix} 0^{++'} \end{bmatrix} = M_0 + \kappa_{12} - 2\kappa_+,
M \begin{bmatrix} 1^{+-'} \end{bmatrix} = M_0 + \kappa_{12} - \kappa_+,
M \begin{bmatrix} 2^{++'} \end{bmatrix} = M_0 + \kappa_{12} + \kappa_+.
\]

It worth mentioning that this splitting scheme agrees with the result of the work \[13\] in which interaction of the total diquark spins was concerned.

To obtain numerical values of tetraquark masses one needs to know the unsplitted mass \(M_0\) and coefficients \(\kappa_{ij}\) in the Hamiltonian \([1]\). These coefficients can be calculated using expressions \([2\) and \(3]\). The following values of quark masses were used:

\[m_c = 1.468\text{ GeV}, \quad m_b = 4.873\text{ GeV}.
\]

Diquark masses without hyperfine splitting are given in \[17\] while \(M_0\) mass of the tetraquark was calculated using a procedure similar to that described in \[17\].

Let us begin with the tetraquark composed of 4 \(c\)-quarks, \(T_{4c} = [cc][\bar{c}\bar{c}]\). Mass of a ground state and value of radial wave function at origin for a \([cc]\) diquark given in \[17\] are

\[m_{cc} = 3.13\text{ GeV}, \quad R_{cc}(0) = 0.523\text{ GeV}^{3/2}.
\]

Value of radial wave function at origin of the \((\bar{c}\bar{c})\) state determined from the leptonic width of \(J/\psi\)-meson equals

\[R_{cc}(0) = 0.75\text{ GeV}^{3/2}.
\]

Spin-spin interaction coefficients calculated using expressions \([2]\) and \(3\) are equal

\[
\kappa_{12} = \kappa_{34} = \kappa_{[cc]} = 12.8\text{ MeV},
\kappa_{13} = \kappa_{23} = \kappa_{14} = \kappa_{24} = \kappa_{[\bar{c}\bar{c}]} = 42.8\text{ MeV}.
\]

Without hyperfine splitting \(T_{4c}\) tetraquark mass equals

\[M_0 = 6.124\text{ GeV},
\]
and with it this state splits into scalar, axial and tensor mesons with masses

\[ 0^{++}: \quad M = 5.966 \text{ GeV}, \quad M - M_{th} = -228. \text{MeV}, \]
\[ 1^{+-}': \quad M = 6.051 \text{ GeV}, \quad M - M_{th} = -142. \text{MeV}, \]
\[ 2^{++}: \quad M = 6.223 \text{ GeV}, \quad M - M_{th} = 29.5 \text{MeV}. \]

In expressions above differences between the tetraquark masses and a \( J/\psi \)-meson pair formation threshold are also noted. It can be seen that only tensor state lies above this threshold and can be observed in the \( T_{bc}(2^{++}) \rightarrow 2J/\psi \) mode. It worth mentioning that scalar tetraquark which is slightly under the \( \psi \) mode. It worth mentioning that scalar tetraquark which is slightly under the \( \mu^+ \mu^- J/\psi \) channel i.e. with one \( J/\psi \)-meson being virtual. So it can be observed as a peak in the \( \mu^+ \mu^- J/\psi \) invariant mass distribution.

For a tetraquark built from 4 \( b \)-quarks, i.e. \( T_{4b} = [bb][bc] \), situation is entirely similar to the previous case. Mass of the \( [bb] \) diquark and values of radial wave function at origin for it and for the \( (bb) \) ground state are

\[ m_{[bb]} = 9.72 \text{ GeV}, \quad R_{[bb]}(0) = 1.35 \text{ GeV}^{3/2}, \quad R_{(bb)}(0) = 2.27 \text{ GeV}^{3/2}. \]

Mass of the \( T_{4b} \) tetraquark without hyperfine splitting is equal to

\[ M_0 = 18.857 \text{ GeV}, \]

and spin-spin interaction coefficients are

\[ \kappa_{12} = \kappa_{34} = \kappa_{[bc]} = 5.52 \text{ MeV}, \]
\[ \kappa_{13} = \kappa_{23} = \kappa_{14} = \kappa_{(bb)} = 27.1 \text{MeV}, \]

With hyperfine splitting one obtains the following masses of the \( T_{4b} \) states:

\[ 0^{++}': \quad M = 18.754 \text{ GeV}, \quad M - M_{th} = -544. \text{MeV}, \]
\[ 1^{+-}': \quad M = 18.808 \text{ GeV}, \quad M - M_{th} = -490. \text{MeV}, \]
\[ 2^{++}: \quad M = 18.916 \text{ GeV}, \quad M - M_{th} = -382. \text{MeV}. \]

It can be seen that in this case all the states are under the \( Y(1S) \) pair production threshold \( M_{th} = 2m_{Y(1S)}. \)

C.  \([bc][bc]\)

The situation is more interesting in the \( T_{2[bc]} = [bc][bc] \) tetraquark case. In this case \([bc] \) diquark spin can be 0 or 1 and all states mentioned in Section II-A exist. Diquark mass and value of its radial wave function at origin are [17]

\[ m_{[bc]} = 6.45 \text{ GeV} \quad R_{[bc]}(0) = 0.722 \text{ GeV}^{3/2}. \]

Radial wave function at origin for the color singlet \((bc)\) state can be determined by its leptonic constant \( f_{B_c} = 500 \text{ MeV} \) [17]:

\[ R_{(bc)} = 1.29 \text{ GeV}^{3/2}. \]

So spin-spin interaction coefficients are equal

\[ \kappa_{12} = \kappa_{34} = \kappa_{[bc]} = 6.43 \text{ MeV}, \]
\[ \kappa_{14} = \kappa_{23} = \kappa_{(bc)} = 27.1 \text{MeV}. \]

Values of \( \kappa_{13} = \kappa_{(bb)} \) and \( \kappa_{24} = \kappa_{(cc)} \) constants were given in expressions [1] and [5]. Without hyperfine splitting \( T_{2[bc]} \) tetraquark mass equals

\[ M_0 = 12.491 \text{ GeV}, \]

and with spin-spin interaction accounted for this state splits (see Fig[1]) into

- Two scalar states with masses

\[ 0^{++}a: \quad M = 12.359 \text{ GeV}, \quad M - M_{th} = -191. \text{MeV}, \]
\[ 0^{++}b: \quad M = 12.471 \text{ GeV}, \quad M - M_{th} = -78.7 \text{MeV}, \]
Two 1+− states with masses

1+−a : \( M = 12.424 \text{ GeV}, \quad M - M_{\text{th}} = -126 \text{ MeV} \)

1+−b : \( M = 12.488 \text{ GeV}, \quad M - M_{\text{th}} = -62.5 \text{ MeV} \)

One 1++ meson with mass

1++ : \( M = 12.485 \text{ GeV}, \quad M - M_{\text{th}} = -64.9 \text{ MeV} \)

One tensor meson with mass

2++ : \( M = 12.566 \text{ GeV}, \quad M - M_{\text{th}} = 16.1 \text{ MeV} \)

Mass of the two \( B_c \) mesons is selected for the threshold value in these expressions, \( M_{\text{th}} = 2m_{B_c} = 12.55 \text{ GeV} \). It can be seen that only tensor tetraquark \( T_{2[bc]}(2^{++}) \) lies above this threshold and thus can be observed as a peak in the \( B_c \)-meson pair invariant mass distribution.

In paper [18] tetraquark states were also considered in the framework of diquark model. Picture of hyperfine splittings of \( T_{2[b\bar{c}]} \)-tetraquark, presented in this paper is in good agreement with our results. Predictions for masses, on the other hand, are about 700 MeV higher, than our values. As a result, according to this paper all tetraquark states should lie above \( 2B_c^* \) and \( J/\psi \Upsilon \) thresholds. We think, that the main reason for difference between these two works is the neglection of binding energy in tetraquark tetraquark and diquark spectra, that is negative. For example, for tetraquark state before hyperfine splitting we have \( \delta E = M_0 - 2m_{[bc]} \approx 410 \text{ MeV} \).

### III. PRODUCTION

#### A. Duality relations

Duality relations can be used to estimate production cross sections of the particles in question. Let us consider formation of two diquarks in gluon interaction \( gg \to [Q_1Q_2][\bar{Q}_3\bar{Q}_4] \). Above the 2 doubly-heavy baryon production...
threshold these diquarks can hadronize into 4 open heavy flavor mesons, 2 heavy quarkonia or form a bound state, i.e. tetraquark. According to our estimations this tetraquark would preferably decay into a vector quarkonia pair. Indeed, decay into light mesons is suppressed by the Zweig rule, production of 4 open heavy flavor mesons is prohibited kinematically and formation of pseudoscalar quarkonia requires flip of the heavy quark spin. That is why the following duality relation can be written:

\[ S_T = \int \frac{2M_{QQ}}{2M_Q} dm_{gg} \hat{\sigma}[gg \rightarrow T \rightarrow 2Q] = \epsilon \int \frac{2M_{QQ}}{2m_{(QQ)}} dm_{gg} \hat{\sigma}(gg \rightarrow [Q_1Q_2] + [\bar{Q}_3\bar{Q}_4]), \] (6)

where \( \epsilon \) factor stands for the other possible decay modes. This value is to be compared with the integrated non-resonant cross section of quarkonia pairs production in the same duality window:

\[ S_{2Q} = \int \frac{2M_{QQ}}{2M_Q} dm_{gg} \hat{\sigma}[gg \rightarrow 2Q]. \] (7)

As tetraquark states are typically narrow, these mesons can be observed as peaks in the quarkonia pairs invariant mass distributions despite that \( S_T \ll S_{2Q} \) relation holds. As tetraquark width is small compared to the detector resolution \( \Delta \approx 50 \text{ MeV} \), its peak can be modeled by a Gaussian form with corresponding width. Therefore cross section of the \( gg \rightarrow T \rightarrow 2Q \) Breit-Wigner process is replaced with the following expression:

\[ \hat{\sigma}(gg \rightarrow T \rightarrow 2Q) = \frac{S_T}{\sqrt{\pi} \Delta} \exp \left\{ -\frac{(m_{gg} - M_T)^2}{\Delta^2} \right\}, \]

where preexponential factor is selected according to the duality relation (6).

**B. \( T_{4c} \)**

Let us begin with the tetraquarks composed of the 4 identical quarks. In the \( T_{4c} \) case only tensor state lies above the 2 vector charmonia production threshold. Integrated cross sections calculated using expressions (6) and (7) are equal

\[ S_{T_{4c}} = 0.7 \text{ pb GeV} \quad S_{2J/\psi} = 20 \text{ pb GeV}, \]

where suppression factor is selected to be \( \epsilon = 0.2 \). Invariant mass distribution for the \( J/\psi \)-meson pairs with expected \( T_{4c} \) tetraquark contribution is shown in Fig. 2.

As already mentioned, in the \( T_{4b} \) tetraquark case even tensor state is under the two vector bottomonia formation threshold so its observation in their invariant mass distribution is doubtful.
timeson pairs invariant mass distribution. However Figure 3. Invariant mass distribution of $B_c$ into $T$ hyperfine splitting accounted for diquarks: in the antitriplet color configuration total spin of the reaction $gg \rightarrow T$ observed at LHC in their invariant mass distribution. For the charmed tetraquark case only tensor meson lies above the vector meson pair formation threshold and its peak can be experimentally observed. Thus tensor tetraquark is shown in Fig. 3a. All states arise after $T_{2[bc]}$ tetraquark is assumed to consist of two $B_c$-meson pairs with expected contribution of the $T_{2[bc]}$ tetraquark is shown in Fig. 3b. All $T_{2[bc]}$ mesons lie under the $B_c^*$ pair production threshold. Decay of the $T_{2[bc]}$ tetraquark into the $J/\psi \Upsilon(1S)$ vector quarkonia pair is also possible. In the color singlet model reaction $gg \rightarrow J/\psi \Upsilon(1S)$ is prohibited so accounting for octet components of vector quarkonia is needed. This process was elaborated in the work [20] results of which are used as the background for the tetraquark contribution. Suppression factor $\epsilon \sim 3 \times 10^{-2}$ was used to obtain integrated cross sections \ref{eq:9} and \ref{eq:10}:

$$S_{T_{2[bc]}} = 0.13 \text{ fb GeV} \quad S_{2B_c} = 6 \text{ fb GeV},$$

where $M_{\Xi_{bc}} = 6.82 \text{ GeV}$ [19] is used. Invariant mass distribution of the $B_c$-meson pairs with expected contribution of the $T_{2[bc]}$ tetraquark is shown in Fig. 3b. All $T_{2[bc]}$ mesons lie under the $B_c^*$ pair production threshold.

Integrated cross sections \ref{eq:9} and \ref{eq:10} are equal

$$S_{T_{2[bc]}} = 1.5 \text{ fb GeV}, \quad S_{\psi\Upsilon} = 33 \text{ fb GeV}.$$
In the last section we estimated the possibility to observe tetraquarks concerned in the inclusive reactions $gg \to T \to 2Q$. According to our calculations $T_{4c}(2^{++})$ tensor state can be observed as a peak in the $J/\psi$-meson pairs invariant mass distribution. $T_{2bc}(2^{++})$ tetraquark can be observed in both $2B_c$ and $J/\psi \Upsilon(1S)$ modes.

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[1] R. L. Jaffe, Phys.Rev. D15, 267 (1977).
[2] R. L. Jaffe, Phys.Rev. D15, 281 (1977).
[3] L. Maiani, F. Piccinini, A. Polosa, and V. Riquer, Phys.Rev. D71, 014028 (2005), hep-ph/0412098.
[4] S. S. Gershtein, A. K. Likhoded, and A. V. Luchinsky, Phys. Rev. D74, 016002 (2006), hep-ph/0602048.
[5] N. Mathur et al., Phys. Rev. D76, 114505 (2007), hep-ph/0607110.
[6] S. Prelovsek et al., PoS LAT2009, 103 (2009), arXiv:0910.2749.
[7] V. M. Abazov et al. (D0), Phys. Rev. Lett. 93, 162002 (2004), hep-ex/0405004.
[8] B. Aubert et al. (BABAR), Phys. Rev. D71, 071103 (2005), hep-ex/0406022.
[9] E. S. Swanson, Phys. Rept. 429, 243 (2006), hep-ph/0601110.
[10] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Lett. B634, 214 (2006), hep-ph/0512230.
[11] K. F. Chen et al. (Belle), Phys. Rev. Lett. 100, 112001 (2008), arXiv:0710.2577.
[12] I. Adachi et al. (Belle), Phys. Rev. D82, 091106(R) (2010), arXiv:0808.2445.
[13] A. Ali, C. Hambrock, and M. J. Aslam, Phys. Rev. Lett. 104, 162001 (2010), arXiv:0912.5016.
[14] A. Ali, C. Hambrock, and W. Wang (2011), arXiv:1110.1333.
[15] A. Berezhnoy, A. Likhoded, A. Luchinsky, and A. Novoselov (2011), arXiv:1101.5881.
[16] K. Terasaki, Prog.Theor.Phys. 125, 199 (2011), arXiv:1008.2992.
[17] V. Kiselev, A. Likhoded, O. Pakhomova, and V. Saleev, Phys.Rev. D66, 034030 (2002), hep-ph/0206140.
[18] A. Ali, C. Hambrock, I. Ahmed, and M. J. Aslam, Phys. Lett. B684, 28 (2010), arXiv:0911.2787.
[19] V. Kiselev and A. Likhoded, Phys.Usp. 45, 455 (2002), hep-ph/0103169.
[20] P. Ko, C. Yu, and J. Lee, JHEP 1101, 070 (2011), arXiv:1007.3095.