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Heavy tetraquarks production at the LHC

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In the current work, spectroscopy and the possibility of observation at the LHC of tetraquarks composed of four heavy quarks are discussed. The 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 the nonrelativistic Schrödinger equation, masses of these states are found with the hyperfine splitting that is 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 $pp \to T_{4c} + X \to 2J/\psi + X$, $pp \to T_{2[bc]} + X \to 2B_c + X$ and $pp \to T_{2[bc]} + X \to J/\psi \Upsilon(1S) + X$ channels, while T_{4b} is under the threshold of decay into a vector bottomonia pair.

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I. INTRODUCTION

Recent observation of J/ψ-meson pairs production in proton-proton collisions at 7 TeV energy at LHC renewed interest in the four 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. Therefore, we would like to discuss the physics of these states and elaborate on their mass spectrum and the possibility of experimental observation.

The conception of tetraquarks, i.e., mesons composed of four valent quarks ($qq\bar{q}\,\bar{q}$), was first introduced in works [1,2] in 1976. For example, a_0 meson and σ mesons were treated as possible tetraquark candidates [3–10]; however, it is hard to determine quark composition of a particle in the light meson domain so these ideas were not developed further. The observation of new unexpected states such as $X(3872)$ [11,12], gave this idea a new impetus [4,13,14]. Eccentricity of these particles consists in the fact that according to the modes of their production and decay they contain a $c\bar{c}$ pair but they cannot be included in the well-known systematics of charmonia. Later, similar particles were also found in the bottomonia sector [15–18]. It is natural to ascribe these mesons to tetraquarks ($Qq\bar{Q}\,\bar{q}$), where q and Q are light and heavy (b or c) quarks, respectively.

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

In our recent paper [19], we considered tetraquark $T_{4c} = [cc][\bar{c}\,\bar{c}]$ in the framework of a diquark model. The hyperfine splitting in that paper was described through interaction of total diquark spins. Now we would like to also study 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 built 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 discussed. The possibility of observation of these particles in hadronic experiments is discussed in the third section, and we summarize our results in the short conclusion.

II. SPECTROSCOPY

A. General preliminaries

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

$$T = Q_1 Q_2 \bar{Q}_3 \bar{Q}_4$$

consists of two almost pointlike diquarks, $\bar{\mathcal{D}}_{12} = [Q_1 Q_2]$ and $\mathcal{D}_{34} = [\bar{Q}_3 \bar{Q}_4]$, with certain quantum numbers (such as angular momentum, spin, color) and mass. In reference to the color configuration, two quarks in the diquark can be in triplet or sextet color state. According to Ref. [20], 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. In reference to the diquark mass, it can be determined by solving the Schrödinger equation with a correctly selected potential. According to Ref. [21], it is possible to use quark-antiquark interaction potential

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used in heavy quarkonia calculations with an additional factor of $1/2$ due to the different color structures.

In the diquark model, tetraquark mass can be determined by solving a two-particle Schrödinger equation with point-like diquarks. As $[Q_1Q_2]$ and $[\bar{Q}_3\bar{Q}_4]$ diquarks are in (anti) triplet color configuration, the 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 [4]

$$H = M_0 + 2\sum_{i<j}\kappa_{ij}(\mathbf{S}_i\mathbf{S}_j), \tag{1}$$

where M_0 is the tetraquark mass without splitting, $\mathbf{S}_i$ is the spin operator of ith (anti)quark, and κ_{ij} are constants determined from experimental data analysis or theory. When dealing with potential models, the κ_{ij} coefficient can be obtained from the value of the Q_iQ_j system wave function at the origin

$$\kappa_{ij} = \frac{1}{2}\frac{4}{9m_{Q_1}m_{Q_2}}\alpha_s|R_{[ij]}(0)|^2 \tag{2}$$

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

$$\kappa_{ij} = \frac{1}{2}\frac{8}{9m_{Q_1}m_{Q_2}}\alpha_s|R_{(ij)}(0)|^2 \tag{3}$$

if Q_i and Q_j are quark and antiquark in color singlet configuration. A three loop expression for the strong coupling constant was used when calculating κ_{ij} constants [21] and scale for it was taken to be equal to

$$\mu^2 = \frac{2m_{Q_1}m_{Q_2}}{m_{Q_1} + m_{Q_2}}\langle T\rangle,$$

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

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

and

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

for the triplet and singlet states, respectively. The values of diquark wave functions in the origin are presented in Ref. [21], while for mesons they can be calculated from the leptonic width Γ_{ee} or leptonic constant f of the meson in question:

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

If one neglects hyperfine splitting, tetraquark can be described by its total spin J; spins of diquarks S_{12}, S_{34}; spatial and charge parities P and C:

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

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:

$$M(1^{++}) = \langle 1^{++}|H|1^{++}\rangle = M_0 - \kappa_{12} - \kappa_-,$$
$$M(2^{++}) = 2m_{[12]} + \kappa_{12} + \kappa_+,$$

where the following designations are introduced,

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

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

$$H\begin{bmatrix} |0^{++}\rangle \\ |0^{++\prime}\rangle \end{bmatrix} = \begin{bmatrix} M_0 - 3\kappa_{12} & -\sqrt{3}\kappa_- \\ -\sqrt{3}\kappa_- & M_0 + \kappa_{12} - 2\kappa_+ \end{bmatrix} \times \begin{bmatrix} |0^{++}\rangle \\ |0^{++\prime}\rangle \end{bmatrix},$$

and for $|1^{+-}\rangle$ tetraquarks,

$$H\begin{bmatrix} |1^{+-}\rangle \\ |1^{+-\prime}\rangle \end{bmatrix} = \begin{bmatrix} M_0 - \kappa_{12} + \kappa_- & \kappa_{13} - \kappa_{24} \\ \kappa_{13} - \kappa_{24} & M_0 + \kappa_{12} - \kappa_+ \end{bmatrix} \times \begin{bmatrix} |1^{+-}\rangle \\ |1^{+-\prime}\rangle \end{bmatrix}.$$

B. $[QQ][\bar{Q}\bar{Q}]$

In the case where quarks of the same flavor are involved, Fermi-Dirac statistics lead to the additional restrictions on the diquark quantum numbers. Indeed, permutation of quark indices should change the sign of the total diquark wave function. As quarks are in the antitriplet color state, the color part of this function is antisymmetric. The radial wave function is symmetric as quarks are in the S wave, so the 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 $|0^{++\prime}\rangle$, $|1^{++\prime}\rangle$, 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 to

$$M(0^{++\prime}) = M_0 + \kappa_{12} - 2\kappa_+,$$
$$M(1^{+-\prime}) = M_0 + \kappa_{12} - \kappa_+,$$
$$M(2^{++}) = M_0 + \kappa_{12} + \kappa_+.$$

It is worth mentioning that this splitting scheme agrees with the result of the work [19] regarding interaction of the total diquark spins.

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

$$m_c = 1.468\ \text{GeV}, \qquad m_b = 4.873\ \text{GeV}.$$

Diquark masses without hyperfine splitting are given in [21], while M_0 mass of the tetraquark was calculated using a procedure similar to that described in [21].

Let us begin with the tetraquark composed of four c quarks, $T_{4c} = [cc][\bar{c}\,\bar{c}]$. The mass of a ground state and the value of the radial wave function at the origin for a $[cc]$ diquark given in [21] are

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

The value of the radial wave function at the origin of the $(c\bar{c})$ state determined from the leptonic width of J/ψ meson equals

$$R_{(c\bar{c})}(0) = 0.75\ \text{GeV}^{3/2}.$$

Spin-spin interaction coefficients calculated using expressions (2) and (3) are equal to

$$\begin{aligned} \kappa_{12} &= \kappa_{34} = \kappa_{[cc]} = 12.8\ \text{MeV}, \\ \kappa_{13} &= \kappa_{23} = \kappa_{14} = \kappa_{24} = \kappa_{(c\bar{c})} = 42.8\ \text{MeV}. \end{aligned} \tag{4}$$

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

$$\begin{aligned} &0^{++\prime}\!: M = 5.966\ \text{GeV}, && M - M_{\text{th}} = -228\ \text{MeV}, \\ &1^{+-\prime}\!: M = 6.051\ \text{GeV}, && M - M_{\text{th}} = -142\ \text{MeV}, \\ &2^{++}\!: M = 6.223\ \text{GeV}, && M - M_{\text{th}} = 29.5\ \text{MeV}. \end{aligned}$$

In the expressions above, the differences between the tetraquark masses and a J/ψ-meson pair formation threshold are also noted. It can be seen that only tensor state lies above this threshold and it can be observed in the $T_{4c}(2^{++}) \to 2J/\psi$ mode. However, it is worth mentioning that scalar tetraquark, which is slightly under the J/ψ-pair threshold, can decay by the $T_{4c}(0^{++\prime}) \to (J/\psi)^* J/\psi \to \mu^+\mu^- J/\psi$ channel, i.e., with one J/ψ 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 four b quarks (i.e., $T_{4b} = [bb][\bar{b}\,\bar{b}]$), the situation is entirely similar to the previous case. The mass of the $[bb]$ diquark and the values of the radial wave function at the origin for it and for the $(b\bar{b})$ ground state are

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

The mass of the T_{4b} tetraquark without hyperfine splitting is equal to

$$M_0 = 18.857\ \text{GeV},$$

and the spin-spin interaction coefficients are

$$\begin{aligned} \kappa_{12} &= \kappa_{34} = \kappa_{[bb]} = 5.52\ \text{MeV}, \\ \kappa_{13} &= \kappa_{23} = \kappa_{14} = \kappa_{(b\bar{b})} = 27.1\ \text{MeV}. \end{aligned} \tag{5}$$

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

$$\begin{aligned} &0^{++\prime}\!: M = 18.754\ \text{GeV}, && M - M_{\text{th}} = -544\ \text{MeV}, \\ &1^{+-\prime}\!: M = 18.808\ \text{GeV}, && M - M_{\text{th}} = -490\ \text{MeV}, \\ &2^{++}\!: M = 18.916\ \text{GeV}, && M - M_{\text{th}} = -382\ \text{MeV}. \end{aligned}$$

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

C. $[bc][\bar{b}\,\bar{c}]$

The situation is more interesting in the $T_{2[bc]} = [bc] \times [\bar{b}\,\bar{c}]$ tetraquark case. In this case, $[bc]$ diquark spin can be 0 or 1 and all states mentioned in Sec. II A exist. Diquark mass and value of its radial wave function at the origin are [21]

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

Radial wave function at the origin for the color singlet $(b\bar{c})$ state can be determined by its leptonic constant $f_{B_c} = 500$ MeV [21]:

$$R_{(b\bar{c})} = 1.29\ \text{GeV}^{3/2}.$$

Therefore, spin-spin interaction coefficients are equal to

$$\begin{aligned} \kappa_{12} &= \kappa_{34} = \kappa_{[bc]} = 6.43\ \text{MeV}, \\ \kappa_{14} &= \kappa_{23} = \kappa_{(b\bar{c})} = 27.1\ \text{MeV}. \end{aligned}$$

The values of $\kappa_{13} = \kappa_{(b\bar{b})}$ and $\kappa_{24} = \kappa_{(c\bar{c})}$ constants were given in expressions (4) 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

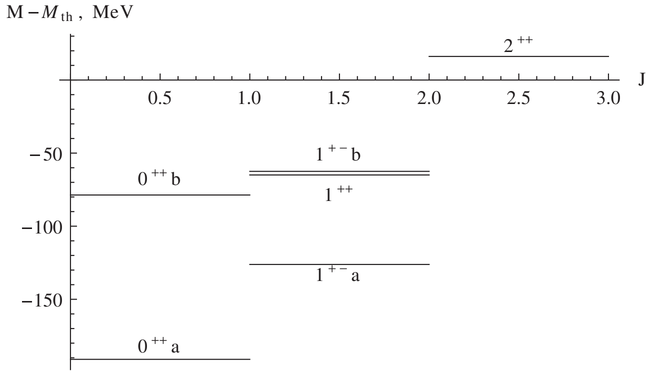

FIG. 1. $[bc][\bar{b}\bar{c}]$ tetraquark mass spectrum.

(i) two scalar states with masses

$$0^{++}a\text{: } M = 12.359 \text{ GeV},$$
$$M - M_{\rm th} = -191 \text{ MeV},$$
$$0^{++}b\text{: } M = 12.471 \text{ GeV},$$
$$M - M_{\rm th} = -78.7 \text{ MeV},$$

(ii) two 1^{+-} states with masses

$$1^{+-}a\text{: } M = 12.424 \text{ GeV},$$
$$M - M_{\rm th} = -126 \text{ MeV},$$
$$1^{+-}b\text{: } M = 12.488 \text{ GeV},$$
$$M - M_{\rm th} = -62.5 \text{ MeV},$$

(iii) one 1^{++} meson with mass

$$1^{++}\text{: } M = 12.485 \text{ GeV},$$
$$M - M_{\rm th} = -64.9 \text{ MeV},$$

(iv) one tensor meson with mass

$$2^{++}\text{: } M = 12.566 \text{ GeV},$$
$$M - M_{\rm th} = 16.1 \text{ MeV}.$$

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

In Ref. [22], tetraquark states were also considered in the framework of a diquark model. The picture of hyperfine splittings of $T_{2[bc]}$ 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 the difference between these two works is the neglect of negative binding energy in tetraquark and diquark spectra. For example, for tetraquark state before hyperfine splitting we have $\delta E = M_0 - 2m_{[bc]} \approx 410$ 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 two doubly heavy baryon production threshold, these diquarks can hadronize into four open heavy flavor mesons, two 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 four open heavy flavor mesons is prohibited kinematically and the formation of pseudoscalar quarkonia requires flip of the heavy quark spin. That is why the following duality relation can be written:

$$S_T = \int_{2M_\mathcal{Q}}^{2M_{\Xi_{QQ}}} dm_{gg}\hat{\sigma}[gg \to T \to 2\mathcal{Q}] = \epsilon \int_{2m_{[QQ]}}^{2M_{\Xi_{QQ}}} dm_{gg}\hat{\sigma}(gg \to [Q_1Q_2] + [\bar{Q}_3\bar{Q}_4]), \quad (6)$$

where ϵ factor stands for the other possible decay modes. It is rather hard to determine this parameter theoretically, so in our paper we will use reasonable assumptions. This integral (6) should be compared with the integrated nonresonant cross section of quarkonia pairs production in the same duality window:

$$S_{2\mathcal{Q}} = \int_{2M_\mathcal{Q}}^{2M_{\Xi_{QQ}}} dm_{gg}\hat{\sigma}[gg \to 2\mathcal{Q}]. \quad (7)$$

As tetraquark states are typically narrow, these mesons can be observed as peaks in the quarkonia pairs invariant mass distributions despite the fact that the $S_T \ll S_{2\mathcal{Q}}$ relation holds. In analogy with known candidates to tetraquark states [e.g., $X(3872)$], we could expect that the widths considered in our article particles are small compared to the detector resolution $\Delta \approx 50$ MeV, so this peak can be modeled by a Gaussian form with corresponding width. Therefore, cross section of the $gg \to T \to 2\mathcal{Q}$ Breit-Wigner process is replaced with the following expression:

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

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

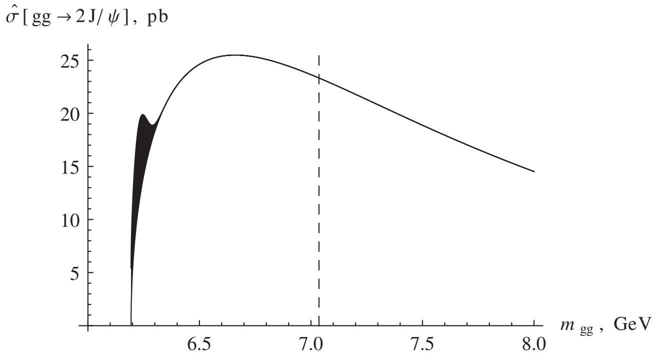

FIG. 2. Invariant mass distribution of J/ψ-meson pairs with expected T_{4c} tetraquark contribution. Dashed vertical line corresponds to the two doubly heavy baryons formation threshold $2M_{\Xi_{cc}}$.

B. T_{4Q}

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

$$S_{T_{4c}} = 0.7 \text{ pb GeV} \qquad S_{2J/\psi} = 20 \text{ pb GeV},$$

where the suppression factor is selected to be $\epsilon = 0.2$. Invariant mass distribution for the J/ψ-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.

C. $T_{2[bc]}$

Let us turn to the $T_{2[bc]} = [bc][\bar{b}\,\bar{c}]$ tetraquark. In this case, pseudoscalar B_c meson and vector B_c^* meson decaying into $B_c\gamma$ can be experimentally observed. Thus, tensor tetraquark $T_{2[bc]}(2^{++})$ can be observed as a peak in the B_c-meson pairs invariant mass distribution. However, $T_{2[bc]}(2^{++}) \to 2B_c$ decay requires flip of the heavy quark spin and is suppressed by the factor

$$\epsilon \sim \frac{M_T - 2m_{[bc]}}{m_{[bc]}} \approx 2.6 \times 10^{-3}.$$

Integrated cross sections (6) and (7) are equal to

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

where $M_{\Xi_{bc}} = 6.82$ GeV [23] is used. Invariant mass distribution of the B_c-meson pairs with expected contribution of the $T_{2[bc]}$ tetraquark is shown in Fig. 3(a). 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, $gg \to J/\psi\Upsilon(1S)$ is prohibited so accounting for octet components of vector quarkonia is needed. This process was elaborated in Ref. [24], the results of which are used as the background for the tetraquark contribution. The suppression factor $\epsilon \sim 3 \times 10^{-2}$ was used to obtain integrated cross sections (6) and (7):

$$S_{T_{2[bc]}} = 1.5 \text{ fb GeV}, \qquad S_{\psi\Upsilon} = 33 \text{ fb GeV}.$$

Invariant mass distribution of the $J/\psi\Upsilon(1S)$ pairs with expected contribution of the $T_{2[bc]}$ tetraquark is shown in Fig. 3(b).

IV. CONCLUSION

In our work, tetraquarks composed of four heavy quarks are studied. Spectroscopy of $T_{4c} = [cc][\bar{c}\,\bar{c}]$, $T_{4b} = [bb][\bar{b}\,\bar{b}]$, and $T_{2bc} = [bc][\bar{b}\,\bar{c}]$ states is elaborated and the possibility of observation at the LHC is studied.

The model used implies diquark structure of tetraquarks; i.e., $Q_1Q_2\bar{Q}_3\bar{Q}_4$ tetraquark is assumed to consist of two almost pointlike diquarks $[Q_1Q_2]$ and $[\bar{Q}_3\bar{Q}_4]$ being in triplet color configuration. In such a treatment, tetraquark is entirely analogous to a doubly heavy meson. So the nonrelativistic Schrödinger equation, which gives reliable results for the charmonia and bottomonia description, can be used to obtain its parameters.

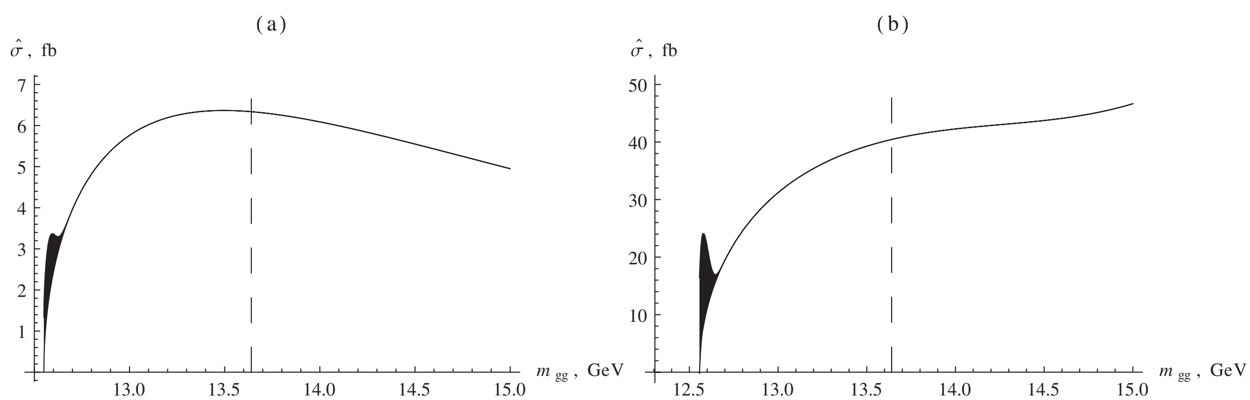

FIG. 3. Invariant mass distribution of B_c-meson pairs (a) and $J/\psi\Upsilon(1S)$ (b) with expected contribution of the $T_{2[bc]}$ tetraquark. Dashed vertical line corresponds to the two doubly heavy baryons formation threshold $2M_{\Xi_{bc}}$.

In the case of T_{4c} and T_{4b} tetraquarks, the Fermi principle imposes constraints on the possible quantum numbers of diquarks: in the antitriplet color configuration, total spin of the S-wave diquark can be only equal to 1. So with the hyperfine splitting accounted for, three states with the following quantum numbers appear: 0^{++}, 1^{+-}, and 2^{++}. In the charmed tetraquark case, only tensor meson lies above the vector meson pair formation threshold and its peak can be observed at LHC in their invariant mass distribution. For the T_{4b} tetraquark, all the states lie under the $\Upsilon(1S)$ pair formation threshold. Both zero and one spins are possible for the diquark in the T_{2bc} tetraquark. So six states arise after the hyperfine splitting of the unaffected state: two of 0^{++}, one 1^{++}, two of 1^{+-}, and one 2^{++}.

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

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