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Production and detection of doubly charmed tetraquarks

A. Del Fabbro,[1] D. Janc,[2] M. Rosina,[2,3] and D. Treleani[1,4]

[1] *INFN, Sezione di Trieste, I-34014 Trieste, Italy*
[2] *Jožef Stefan Institute, Jamova 39, SI-1001 Ljubljana, Slovenia*
[3] *Faculty of Mathematics and Physics, University of Ljubljana, Slovenia*
[4] *Universitá di Trieste, Dipartimento di Fisica Teorica, Strada Costiera 11, Miramare-Grignano, Italy*
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The feasibility of tetraquark detection is studied. For the $cc\bar{u}\,\bar{d}$ tetraquark we show that in present (SELEX, Tevatron, RHIC) and future facilities (LHCb, ALICE) the production rate is promising and we propose some detectable decay channels.

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I. INTRODUCTION

The purpose of this paper is to assess the possibility of detecting certain tetraquarks in present and future facilities. Among many possible tetraquarks, the double charm tetraquark $T_{cc} = cc\bar{u}\,\bar{d} = DD^*$ with quantum numbers $IS^P = 01^+$ is particularly interesting since it is very sensitive to the chosen effective interaction:

(i) It is very delicate; it is either weakly bound or slightly unbound with respect to the two-body hadronic decay $D + D^*$.
(ii) Its structure can be either predominantly "molecular" or predominantly "atomic" with consequences for the production and decay.

Double charm tetraquarks were intensively studied by many authors. Various approaches were applied, from lattice QCD [1] and chiral heavy quark effective theory [2–4] to nonrelativistic potential models [5–8]. It was shown that, although the predictions of these theories agree in the baryon and meson sector, they give dramatically different results for tetraquarks. For this reason, the double charm tetraquarks present an important laboratory for discriminating between different hadronic models.

Moreover, our estimates for the production cross section of such states give us some hope that they can be experimentally detected in near future.

The most important ingredient in the production of the T_{cc} tetraquark is double charm production. Experimental data for such events are very puzzling. The production of prompt J/ψ at B factories [9,10] as well as the production of Ξ_{cc} at SELEX [11] are much larger than expected. Therefore the comparison of T_{cc} production with $J/\psi c\bar{c}$ at B factories and the comparison of T_{cc} production with Ξ_{cc} at SELEX could shed some new light on the mechanism responsible for such a large double charm production.

In Sec. II we present our results for the T_{cc} production at high energy colliders where we believe that the dominant mechanism for the initial double charm production is double gluon fusion. From experimental data we also estimate phenomenologically the production of the T_{cc} tetraquark at B factories and at SELEX. The results of detailed four-body calculations in nonrelativistic constituent quark model (Section III) encourage us to further investigate this state. Since we found the T_{cc} tetraquark to be weakly bound, we propose in Sec. IV the branching ratio between hadronic and radiative decays as the most promising mechanism for the detection of these states.

II. PRODUCTION OF DOUBLE CHARM AT VARIOUS FACILITIES

The most promising mechanism for the production of the T_{cc} tetraquark is the formation of the cc diquark followed by hadronization into $cc\bar{u}\,\bar{d}$. An alternative mechanism would exploit binding of D and D^* mesons if they are produced with small relative momenta. One might expect that the latter mechanism could drastically enlarge the production rate if the dominant configuration is molecular. Because of the very messy environment in hadron colliders, however, such a weakly bound system would too soon dissociate into free mesons by the interaction with surrounding partons of initial hadrons.

The first step is to create two $c\bar{c}$ pairs with the c quarks close in the phase space and in color antisymmetric state, so that in the second step they bind into the cc diquark. The binding energy of a cc diquark in spin 1 and color antitriplet state calculated with the Bhaduri [12] or AL1 nonrelativistic potential models [13] is ~200 MeV [6]. Since nonrelativistic potential models predict too small mass for the Ξ_{cc} state compared with SELEX experiment [13] this suggest even stronger binding for the cc diquark in this state. There were studies of the production of double charm baryons where sextet color and spin zero configuration of the heavy diquark is taken into account [14] as well, which can also be generalized to the production of double charm tetraquarks. The production of double charm baryons by this mechanism is shown to be smaller [14] although significant. We will neglect this mechanism for the T_{cc} production. In the third step the diquark gets dressed either with a light u or d quark into a ccu or ccd baryon or with a light $\bar{u}\,\bar{d}$ antidiquark into the $cc\bar{u}\,\bar{d}$ tetraquark. The probabilities for these two types of dressing can be estimated using the analogy of a single heavy quark fragmentation.

The branching ratio of the $b \to B$ and $b \to \Lambda_b$ production at the Fermilab and at LEP experiment is 0.9 and 0.1, respectively [15]. Therefore we expect the same ratio in the hadronization $cc \to \Xi_{cc}$ and $cc \to T_{cc}$, respectively.

The double charm baryons were probably detected at SELEX [11]. It was estimated that 40% of singly charmed baryons which they have seen, result from the decay of doubly charmed baryons. The most probable mechanism for the double charm production at SELEX is production of the single $c\bar{c}$ pair in the processes $gg \to c\bar{c}$ or $q\bar{q} \to c\bar{c}$ while the second $c\bar{c}$ pair is created in the fragmentation of the heavy quark $c \to cc\bar{c}$. However, theoretically it is still unclear why the SELEX has such a large cross section for double charm production. Since SELEX is a fixed target experiment the cc diquark is most likely to be produced with high lab momenta which might be helpful in the detection as discussed in [16]. But since SELEX found, with their cuts, only about 50 candidates for double charm baryons, the statistics for detecting double charm tetraquarks should be improved.

Next, we look at the production and detection of the T_{cc} tetraquark in Bfactories. Since the total mass of four D mesons is close to the c.m. energy, the c quarks created in this process have small relative momenta which is very important in T_{cc} production. This feature also ensures a smaller number of additional pions created in the e^+e^- annihilation and thus a cleaner reconstruction of T_cc. Belle [9,10] has reported a measurement of prompt J/ψ production in e^+e^- annihilation at $\sqrt{s} = 10.6$ GeV and found that most of the observed J/ψ production is due to the double $c\bar{c}$ production

$$\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$$

which corresponds to [9,10]

$$\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.87^{+0.21}_{-0.19} \pm 0.17 \text{ pb}$$

or to about 2000 events from their 46.2 fb^{-1} data sample. The theoretical nonrelativistic QCD prediction for this process is an order of magnitude smaller [17–20] so this process is still not well understood [21]. However, it is very likely that the analogous mechanism would also enlarge the cross section for the prompt production of cc diquark and thus the Ξ_{cc} baryon and T_{cc} tetraquark. The cc diquark production cross section at B factories is $\sim$0.15 pb as was estimated by Berezhnoy and Likhoded [22] where they obtained it with the method based on factorization theorem and also on the hypothesis of quark-hadron duality. The distribution over invariant mass of the cc pair in color triplet state or $c\bar{c}$ pair in color singlet state coincide with each other for small invariant mass, therefore this estimation is close to the NRQCD prediction for the $J/\psi c\bar{c}$ production at B factories. The number of doubly charmed hadrons produced at this facilities can then be estimated to be $\sim 10^4$ Ξ_{cc} [22] and thus about $\sim 10^3$ T_{cc} per year.

We now present our calculation for the T_{cc} production at high energy colliders. The two colliding nucleons in TeV machines can be considered as two packages of virtual gluons whose number is huge for low Bjorken-x. Therefore we expect [23,24] that in these facilities the dominant mechanism for double charm production would be a disconnected double gluon-gluon fusion: $(g + g) + (g + g) \to (c + \bar{c}) + (c + \bar{c})$.

The usual hard production mechanism is heavy quark production followed by fragmentation; however, this mechanism does not include all the possible Feynman diagrams. In Ref. [23,25,26] it has been shown that at high energy colliders a significant rate of events with double heavy quark pairs is expected. To compute all the fourth order α_s Feynman diagrams we have to consider the two different mechanisms leading to the same final state: the usual single parton scatterings and the double parton scatterings.

In Ref. [25,26] we have shown that double parton scatterings dominate the four heavy quarks ($b\bar{b}b\bar{b}$, $c\bar{c}c\bar{c}$, $c\bar{c}b\bar{b}$) integrated cross section, both in central rapidity region of the ALICE experiment and a larger rapidity values of the LHCb experiment. In both cases it is evident that the single parton scattering term becomes important only after applying cuts to the transverse momenta of the order of 10 GeV. The two colliding nucleons in TeV machines can be considered as two packages of virtual gluons whose number is huge at small x: in fact, the mass of the c-quarks is very small as compared to the center of mass energy and then $x \sim m_c/\sqrt{s} < <1$. Therefore the large parton flux at high energy is dominated by gluons that produce heavy quarks via gluon-gluon fusion. In single parton interactions the leading partonic subprocess is $gg \to c\bar{c}c\bar{c}$, while the leading double parton subprocess is $(g + g) + (g + g) \to (c + \bar{c}) + (c + \bar{c})$, where the two distinct interactions occur in the same hadronic event. Therefore at the LHC experiment, in the multiple heavy quarks production at relatively low momenta, one has to compute all the multiple parton contributions and these contributions give the leading part of the cross section.

We give an estimate of the production cross section at high energy in the region of small transverse momenta where the multiple parton interactions provide the leading contribution to the cross section [25,26]. We compute the production cross section of two c-quarks, c_1, c_2, very close in momentum space $|p_{1j} - p_{2j}| < \Delta$, $j = x, y, z$, as a function of Δ. We consider the heavy quark production in the kinematical range of LHCb ($\sqrt{s} = 14$ TeV, $1.8 < \eta < 4.9$), and for completeness for ALICE ($\sqrt{s} = 14$ TeV, $|\eta| < 0.9$), Tevatron ($\sqrt{s} = 1.8$ TeV, $|y| < 1$) and RHIC ($\sqrt{s} = 200$ GeV, $|\eta| < 1.6$) experiments; in the last case we calculate also the production cross sections in proton-nucleus interactions [27].

We evaluate the double parton scattering cross section at lowest order parton model and then we have to multiply the cross section by a K-factor in order to take into account of QCD higher order corrections. One should notice that the double parton scattering cross section $\sigma_D(c\bar{c}c\bar{c})$ is proportional to the single parton scattering cross section squared, $\sigma_S(c\bar{c})^2$, and therefore one should rescale the lowest order σ_D by a factor K^2. In the calculation we use as the heavy quark mass the value $m_c = 1.4$ GeV and, following [27], the K-factor $K = 6.6$. The results are shown in Fig. 1. One can notice that the cross section $d\sigma/d^3p$ at small Δ is almost uniform therefore it is approximately proportional to the momentum volume Δ^3.

In the second step, the two c quarks join into a diquark. We assume simultaneous production of two independent c quarks with momenta $\mathbf{p}_1$, $\mathbf{p}_2$. Since they appear wherever within the nucleon volume, we modulate their wave functions with a Gaussian profile with the "oscillator parameter" $B = \sqrt{2/3}\sqrt{<r^2>} = 0.69$ fm corresponding to the nucleon rms radius

$$\mathcal{N}_B e^{-r_1^2/2B^2 + i\mathbf{p}_1\cdot\mathbf{r}_1} \mathcal{N}_B e^{-r_2^2/2B^2 + i\mathbf{p}_2\cdot\mathbf{r}_2} \equiv \mathcal{N}_{(B/\sqrt{2})} e^{-R^2/2(B/\sqrt{2})^2 + i\mathbf{P}\cdot\mathbf{R}} \mathcal{N}_{(B\sqrt{2})} e^{-r^2/2(B\sqrt{2})^2 + i\mathbf{p}\cdot\mathbf{r}}$$

where the normalization factor is $\mathcal{N}_\beta = \pi^{-3/4}\beta^{-3/2}$. In the case of the nucleon-nucleus collision, we must take into account the possibility that the double gluon fusion occurs on two neighboring nucleons in the target. The above equation transforms now into

$$\mathcal{N}_{(B/\sqrt{2})} e^{-R^2/2(B/\sqrt{2})^2 + i\mathbf{P}\cdot\mathbf{R}} \mathcal{N}_{(B\sqrt{2})} e^{-(\mathbf{r}-\mathbf{r}_a)^2/2(B\sqrt{2})^2 + i\mathbf{p}\cdot\mathbf{r}}$$

Here $\mathbf{r}_a$ is the average distance between two nucleons in the target nucleus. For proton-gold experiment at RHIC which is of the great importance for us, this mechanism contributes two thirds to the total cross section, while the remaining is due to the double charm production on the same nucleon in the target. We use the value $r_a = 2.4$ fm.

We make an impulse approximation that this two-quark state is instantaneously transformed in any of the eigenstates of the two-quark Hamiltonian. Then the amplitude of the diquark formation M is equal to the overlap between the two free quarks and the diquark with the same center-of-mass motion. By approximating the diquark wave function with a Gaussian with the oscillator parameter $\beta = 0.41$ fm we get

$$M(p) = \int d^3r \mathcal{N}_{B\sqrt{2}} e^{-(\mathbf{r}-\mathbf{r_a})^2/2(B\sqrt{2})^2 - i\mathbf{p}\cdot\mathbf{r}} \mathcal{N}_\beta e^{-r^2/2\beta^2}$$

For the production cross section we take into account that $d\sigma/d^3p$ is practically constant and can be taken out of the integral

$$\sigma = \frac{3}{9}\cdot\frac{3}{4}\cdot\int d^3p \frac{d\sigma}{d^3p} M^2(p) \approx \frac{1}{4}\frac{d\sigma}{d^3p}\left(\frac{2\sqrt{\pi}\hbar}{\sqrt{2B^2+\beta^2}}\right)^3 e^{-r_a^2/2B^2}$$

where factors in front of the integral are due to the projection on the color and spin triplet states. If we insert the values of $d\sigma/dp^3$ obtained from Fig. 1, we get $\sigma \approx 27$ nb and 58 nb for LHCb and ALICE at LHC, $\sigma \approx 21$ nb at Tevatron and $\sigma \approx 4$ nb and 755 nb at RHIC for proton-proton and proton-gold interaction, respectively.

The last step of the T_{cc} production is dressing of the heavy diquark. It either acquires one light quark to become the doubly-heavy baryon ccu, ccd or ccs, or two light antiquarks to become a tetraquark. With this we neglect the possible dissociation of the heavy diquark into a DD pair so the results are an upper estimate for real T_{cc} production. Little is known about the mean free path of the diquark inside the colliding hadrons. We expect that at least those formed near the surface of the nucleon survive. We assume that the probability for dressing the cc diquark into the $cc\bar{u}\bar{d}$ tetraquark is 0.1 [15], as pointed out at the beginning of the section. Our estimates for the production rates of the T_{cc} tetraquark at LHC, Tevatron and RHIC are listed in Table I.

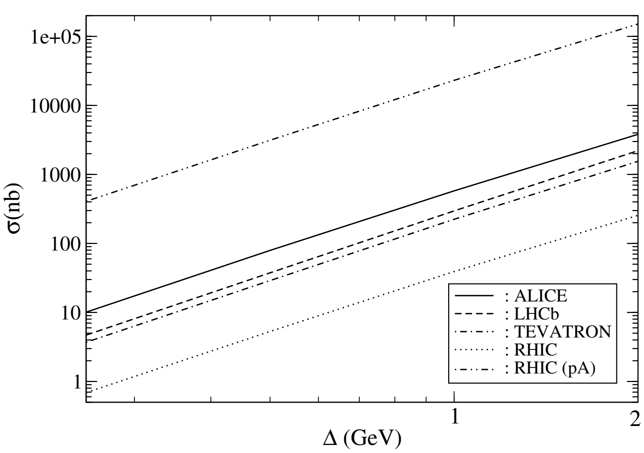

FIG. 1. Production cross section of two c quarks in momentum space Δ at LHC (LHCb and ALICE), at Tevatron and at RHIC.

III. STRUCTURE OF T_{cc}

The structure of the T_{cc} tetraquark has been studied in Ref. [28]. We summarize here those features which are particularly relevant for the detection.

There are two extreme spatial configurations of quarks in a tetraquark. The first configuration which we call *atomic* is similar to $\bar{\Lambda}_c$, with a compact cc diquark instead of $\bar{c}$, around which the two light antiquarks are moving in a similar manner as in the $\bar{\Lambda}c$ baryon. The second configuration which we call *molecular* resembles deuteron, the two heavy quarks are well separated and the two light antiquarks are bound to them as if we had two almost free mesons. The atomic configuration is more likely to appear in strongly bound tetraquarks while the molecular configuration can be expected in weakly bound systems.

TABLE I. Estimations for the T_{cc} tetraquark production at various facilities. At RHIC experiment, the results are for scattering of the nucleon on gold. Production rate for the gold-gold scattering is due to the small luminosity significantly smaller. Estimate for production at SELEX and in Belle B factory are obtained from experimental data on double charm production.

	LHC LHCb	ALICE	Tevatron	RHIC	SELEX	Belle
Luminosity ($cm^{-2}s^{-1}$)	10^{33}	10^{33}	8×10^{31}	2×10^{27}		
Cross section (nb)	27	58	21	755		
No. of events	9700/hour	20900/hour	600/hour	12/hour	5	1000/year

We present results using two different one-gluon exchange potentials. The Bhaduri potential [12] quite successfully describes the spectroscopy of the meson, as well as baryon ground states. This is an important condition since in the tetraquark we have both quark-quark and quark-antiquark interactions. The AL1 potential [13] slightly improves the meson spectra by introducing a mass-dependent smearing of the color-magnetic term.

We expand tetraquark wave function with Gaussinas of three sets of Jaccobi coordinates. In this basis we were able to reconstruct the wave functions of deeply bound tetraquarks as well as of two free mesons - the threshold state. This is important if one is searching for weakly bound tetraquarks with molecular structure. We found that the T_{cc} is weakly bound for both the Bhaduri and AL1 potential in contrast to the results of calculations in harmonic oscillator basis [7] where asymptotic channel cannot be accommodated as shown in Table II.

In Fig. 2 we present the probability densities ρ_{ij} for finding (anti)quark i and (anti)quark j at the interquark distance r_{ij} and the ratio of the projections on color sextet state $|6_{12}\bar{6}_{34}\rangle_C$ and color triplet state $|\bar{3}_{12}3_{34}\rangle_C$ where, e.g.,

$$\rho_{ij}^{(\text{trip.})}(r) = \langle\psi|\bar{3}_{12}3_{34}\rangle_C\langle\bar{3}_{12}3_{34}|_C\delta(r - r_{ij})|\psi\rangle.$$

Here particles 1 and 2 are the two heavy quarks c and particles 3 and 4 the light antiquarks $\bar{u}$ and $\bar{d}$. The wave function between heavy quarks is broad and has an exponential tail $\sim\exp(-\kappa r)$ at large distances where $\kappa = \sqrt{|E_b|M_{red}}/\hbar c$, E_b is the binding energy of the system and M_{red} the reduced mass of the D and D^* mesons. At small distances the dominant color configuration is $\bar{3}_{12}3_{34}$. Here we have a diquark-antidiquark structure and this region present about a third of the total probability while for $r > 1$ fm sextet color configuration become larger. The ratio of these two configurations stabilizes at 2, since here we have a molecular structure of the two color singlet mesons which has in diquark-antidiquark basis the $|1_{13}1_{24}\rangle = \sqrt{1/3}|\bar{3}_{12}3_{34}\rangle + \sqrt{2/3}|6_{12}\bar{6}_{34}\rangle$ color decomposition, while the octet configuration $|8_{13}8_{24}\rangle = -\sqrt{2/3}|\bar{3}_{12}3_{34}\rangle + \sqrt{1/3}|6_{12}\bar{6}_{34}\rangle$ is negligible.

TABLE II. Column 1: type of potential, Column 2: lowest meson-meson threshold for a given potential in MeV, Column 3: our results in MeV, Column 4: results in MeV of Ref. [7,8], Column 5: mean distance in fm between two heavy quarks $\langle r_{cc}\rangle$.

	threshold	our calc.	Ref.[7,8]	$\langle r_c c\rangle$
Bhaduri	3905.3	3904.7	3931	2.4
AL1	3878.6	3875.9	3892	1.6

Now we show that additional weak three-body interaction can transform the molecular structure of the T_{cc} tetraquark into atomic. For the radial part we take the simplest possible radial dependence—the smeared delta function of the coordinates of the three interacting particles [28]. The color factor in the two-body Bhaduri or AL1 potential is proportional to the first (quadratic) Casimir operator $C^{(1)}$;

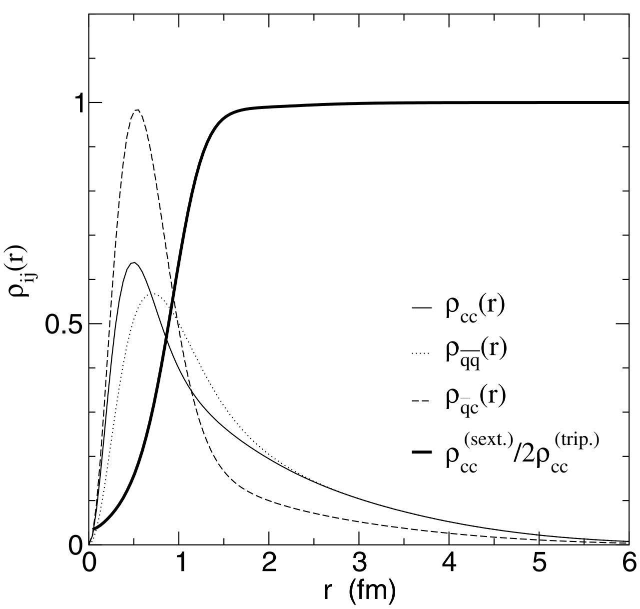

FIG. 2. Results for the AL1 potential: probability density between two heavy quarks $\rho_c c$, between two light antiquarks $\rho_{\bar{q}\bar{q}}$ and between a light antiquark and a heavy quark $\rho_{\bar{q}c}$ in T_{cc} as a function of the interquark distance. The ratio of the projection on color sextet and color triplet configurations is also shown.

$C^{(1)} = \lambda \cdot \lambda$. It is then natural that we introduce in the three-body potential the second $C^{(2)}$ (cubic) Casimir operator $C^{(2)} = d^{abc}\lambda_a \cdot \lambda_b \cdot \lambda_c$. A deeper discussion of the properties that the color dependent three-body interaction must fulfil can be found in [29–31].

In the baryon sector the three-body interaction was used to better reproduce the baryon ground state spectroscopy [13]. A color structure is there irrelevant since there is only one color singlet state and thus the color factor is just a constant which can be included into the strength of the potential. In tetraquarks the situation is different since there are two color singlet states: $\bar{3}_{12}3_{34}$ and $6_{12}\bar{6}_{34}$ (or $1_{13}1_{24}$ and $8_{13}8_{24}$ after recoupling). The three-body force operates differently on these two states and one can anticipate that in the case of the weak binding it can produce large changes in the structure of the tetraquark. This cannot be otherwise produced simply by reparametrization of the two-body potential, so the weakly bound tetraquarks are a very important laboratory for studying the effect of such an interaction.

A drastic change in the width of the probability density can already be seen for strength $U_0 = -20$ MeV (Fig. 3), where the binding energy of the tetraquark becomes -14 MeV for Bhaduri potential. Here T_{cc} loses the molecular structure, the triplet-triplet color configurations become dominant and the T_{cc} tetraquark becomes similar to T_{bb}. In the baryon sector such an interaction would merely lower the states by about U_0 so it would have no dramatic effect nor would it spoil the fit to experimental data. Since the predicted energies of ground state baryons for the Bhaduri and AL1 potential are above the experimental values, this is actually a desirable feature.

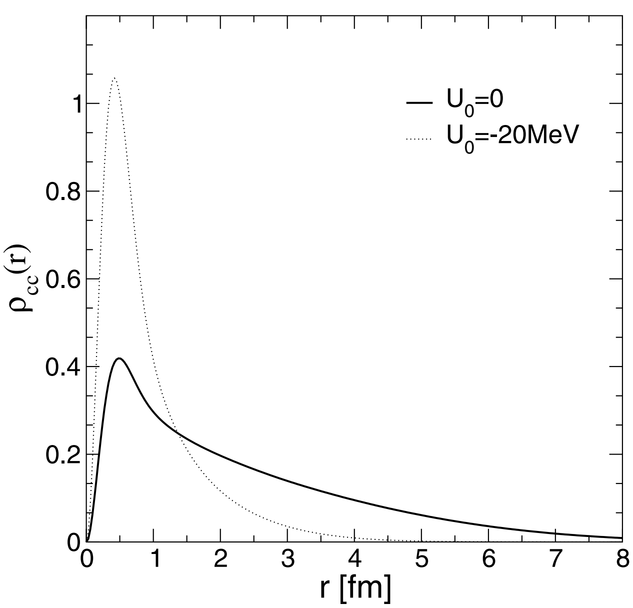

FIG. 3. Results for the Bhaduri potential: probability density between two c quarks ρ_{cc} in the T_{cc} tetraquark as a function of interquark distance for two different values of the strength of the three-body potential.

IV. DETECTION

In order to identify a weakly bound T_{cc} tetraquark we have to distinguish the pion or photon emitted by the D^* meson bound inside the tetraquark from the one resulting from free D^* meson decay. We can exploit the fact that the phase space for $D^* \to D + \pi$ decay is very small. This has a strong impact on the branching ratio between radiative and hadronic decay. Since the D^* meson inside the tetraquark with molecular structure is not significantly influenced by the other D meson in the tetraquark, we expect that the partial width for the magnetic dipole M1 transition would be very close to the width of the free meson while the width for hadronic $D^* \to D + \pi$ decay will decrease with stronger binding and will become energetically forbidden below the $D + \pi$ threshold. The hadronic decay of the T_cc tetraquark is a three-body decay which is commonly represented by the Dalitz plot.

If the T_{cc} tetraquark is below the $D + D^*$ threshold but above the $D + D + \gamma$ and $D + D + \pi$, as was the case in our nonrelativistic potential models, the partial decay rate for the $T_{cc} \to D + D + \pi$ is given by

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2 dm_{23}^2 \tag{1}$$

where particles 1 and 2 are two final D mesons and particle 3 is the pion emerging from the decaying tetraquark. Here $m_{12}^2 = (p_D + p_D)^2$ and $m_{23}^2 = (p_D + p_\pi)^2$ and M is the mass of the tetraquark. Since the total masses of the $D^* + D$ and $2D + \pi$ are so close there is a strong isospin violation in the decay which cannot be reproduced with the Bhaduri or AL1 potential where the D^* and the D isospin doublets are degenerate. We shall not try to modify the interaction to accommodate the dependence of the decay on the isospin of the particles, but we shall rather work with the experimental masses taken from the PDG [32] where we see that $m_{D^{*+}} - m_{D^+} - m_{\pi^0} = 5.6 \pm 0.1$ MeV, $m_{D^{*0}} - m_{D^0} - m_{\pi^0} = 7.1 \pm 0.1$ MeV, $m_{D^{*+}} - m_{D^0} - m_{\pi^+} = 5.87 \pm 0.02$ MeV. Let us consider the decay $T_{cc}^+ \to D^+D^0\pi^0$. The allowed region of integration over dm_{12}^2 and dm_{23}^2 for three different binding energies of the T_{cc}^+ is plotted in Fig. 4. We have now actually here two thresholds to which we can define the binding energy, the $D^{0*}D^+$ and D^0D^{+*} at 3876.1 ± 1 MeV and 3874.6 ± 1 MeV, respectively. Since due to the experimental uncertainty of D meson masses, we can neglect this and take for the threshold the average value of 3875.4 MeV. If we assume that $\overline{|\mathcal{M}|^2}$ is constant, which is very plausible in our case, the allowed region will be uniformly populated with experimental events so that the measured partial decay rate Γ will be proportional to the kinematically allowed area from Fig. 4. This is shown in

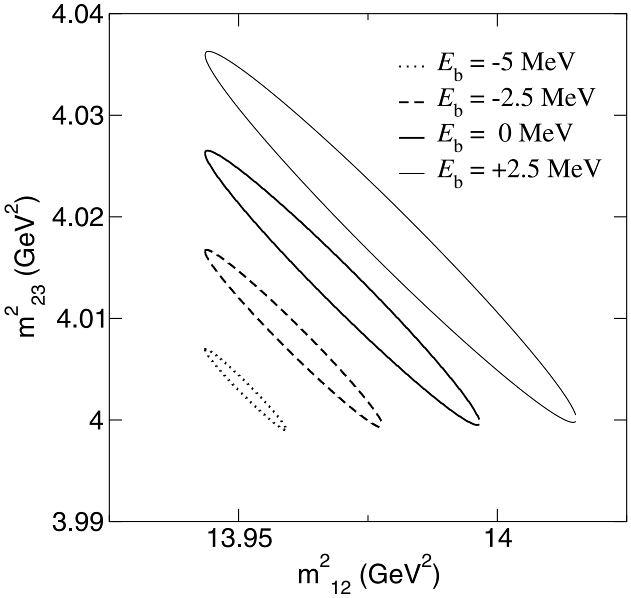

FIG. 4. Dalitz plot for four different values of the binding energy $E_{\rm b}$.

Fig. 5, where we assumed that for the molecular state, the width of the T_{cc} tetraquark with zero binding energy would be the same as the width of the free D^* meson.

Let us now consider also the possibility that T_{cc} is not a bound DD^* state but a resonant state above the $D + D^*$ threshold. Here will appear also the two-body decay $T_{cc} \rightarrow D + D^*$ beside the three-body $T_{cc} \rightarrow D + D + \pi$ decay. To obtain the branching ratio between these two mechanisms, we must somehow estimate the decay width for the two-body decay, while the decay width for the three-body decay can be deduced from the Dalitz plot Fig. 5 for the given positive binding energy. We exploit the analogy with the charmonium $\psi(3770)$ state, which is also a resonance, situated 36 MeV above the $\bar{D}D$ threshold into which it dominantly decays. The width of this state is 25.3 ± 2.9 MeV. Let us assume, that the T_{cc} tetraquark is also 36 MeV above the $D + D^*$ threshold and that its decay width for the two-body decay is the same as for the $\psi(3770)$ resonance, since the masses of the final particles are similar. The width for the three-body decay is proportional to the area of the Dalitz plot at the binding energy $E_b = +36$ MeV which is 37 times greater than the area at the threshold $E_b = 0$. Since we normalized the decay width at $E_b = 0$ to be equal to the decay width of the free D^* meson, which is according to the PDG [32] $\Gamma(D^* \rightarrow D\pi) = 96 \pm 4 \pm 22$ keV we can estimate that the the decay width for the $T_{cc} \rightarrow D\pi D$ three-body decay would be $\Gamma \sim 37 \cdot 96$ keV $= 3.6$ MeV. We thus expect the branching ratio for $T_{cc} \rightarrow D\pi D$ and $T_{cc} \rightarrow D^*D$ to be 3.6 MeV /25 MeV = 0.15. The Dalitz plot for the T_{cc} resonance would not be uniformly populated but there will be a strong band where $m_{23} = m_{D^*}$ reflecting the appearance of the $T_{cc} \rightarrow DD^* \rightarrow D(\pi D)$ decay chain. In this estimation we have neglected the interference between these two decay mechanisms, since the width of the D^* is 2 orders of magnitude smaller than the width of the tetraquark if it were 36 MeV above the threshold.

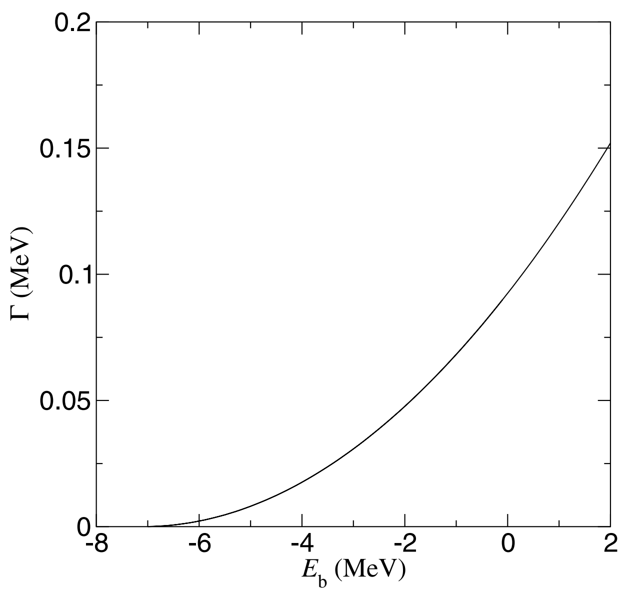

FIG. 5. Width of the T_{cc} tetraquark obtained with integration of the Dalitz plot $\int dm_{12}^2 dm_{23}^2/M^3$ where $M = m_D + m_{D^*} + E_{\rm b}$ is the mass of the tetraquark. The width at $E_b = 0$ is normalized to be equal to the width of the free D^* meson decay.

V. CONCLUSION

We have shown that the T_{cc} tetraquark production is comparable to double charm baryon production (possibly 10%, as suggested by the analogy with the branching ratio $(b \rightarrow \Lambda_b)/(b \rightarrow B)$). Therefore they may be seen in SELEX if statistics is improved. Similarly, it is comparable to prompt $J/\psi c\bar{c}$ production which is reasonably abundant in B-factories. In high energy colliders we may expect an optimistic number of events due to double $c\bar{c}$ production via double two-gluon fusion (see Sec. II). Therefore time has come to start the hunt!

Regarding the detection of the $T_{cc} = DD^*$ tetraquark we propose a nice opportunity—the very small phase space of the $D^* \rightarrow D\pi$ decay which is very sensitive to the binding energy of D^* to D. One possibility would be to measure the branching ratio between the pionic and gamma decay of $T_{cc} = D^*D$, where essentially we have the decay of the bound D^* meson, while the D merely acts as a spectator.

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