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Production of four-quark states with double heavy quarks at LHC

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ABSTRACT

We study the hadronic production of four-quark states with double heavy quarks and double light antiquarks at LHC. The production mechanism involves a color anti-triplet diquark cluster consisting of double heavy quarks that is formed from the double heavy quark-antiquark pairs via the gg fusion hard process first, followed by the fragmentation of the diquark cluster into a four-quark (tetraquark) state. Predictions for the production cross sections and their differential distributions are presented. Our results show that it is promising to discover these tetraquark states in LHC experiments both for large number events and for the unique decay signatures in detectors.

1. Introduction

LHC experiments provide a unique opportunity to explore some exotic states of heavy quarks. Among them, particularly interesting states are the four-quark states consisting of double heavy quarks and double light antiquarks (or their charge conjugator). The existence of such states can be inferred from heavy quark symmetry. The double heavy quarks in the color anti-triplet state may form a diquark cluster by the attractive strong interactions. In the heavy quark limit, the double heavy quarks move slowly, with a small relative velocity v in the rest frame and within a shorter distance $(1/mv)$, compared to the size of the light degree of freedom $(1/\Lambda_{QCD})$. Thus, in the tetraquark states, the double heavy quarks form a color anti-triplet diquark cluster, which contributes color interactions to the double light antiquarks as a color source of a heavy antiquark. The other two light antiquarks move around it with attractive interactions between them. The dynamics of the light degrees of freedom of these tetraquark states are similar to those of heavy baryons. This picture is supported by scrutinizing the typical sizes of real hadrons. The size of the heavy quarkonium is approximately 0.2–0.3 fm, while that of the light hadrons is approximately 1 fm. The masses of such states can be roughly estimated as the sum of the masses of the two heavy quarks and Λ_{QCD}. For the tetraquark states containing the cc, cb, and bb quarks, their masses are approximately 3.4 GeV, 6.8 GeV, and 10.2 GeV, respectively. The flavor features of this sort of hadron are very different from those of the conventional hadrons. Once they are discovered in experiments, it will be evidence for the existence of the tetraquark states. Some theoretical studies on these states have been presented in the literature [1–6].

The spin of a tetraquark state is a composition of the spins of the four quarks and the relative orbital angular momenta between them. For S-waves, all orbital angular momenta vanish. Thus, the spin of the tetraquark state is simply the composition of the spin of each quark or antiquark. The composition of the spins of double heavy quarks may be 0 or 1. However, when two heavy quarks are identical, only the spin 1 state is allowed due to the antisymmetry by exchanging identical fermions. It is the same case for the light antiquarks sector. In this paper, we are interested in only the tetraquark states, in which all orbital angular momenta vanish. We denote these states by $T^i_{Q_1 Q_2}$ $(i = 0, 1)$, where Q_1 and Q_2 represent the heavy flavor indexes, and i is the spin of the double heavy quark subsystem.

As bound states with masses that are quite large, they are difficult to produce in typical high energy machines. Nevertheless, at LHC, they can be produced efficiently via a direct production process that involves effects occurring at several distinct distance scales. First, two heavy quark-antiquark pairs are produced via the gluon–gluon fusion hard subprocess at a distance scale of $1/m$ or shorter. Second, for the two heavy quarks produced that have a small relative velocity v, there are certain probabilities to form a color anti-triplet diquark cluster at a distance scale of $1/mv$.

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Finally, the diquark cluster evolves into the tetraquark state via the fragmentation process by picking up two light antiquarks from the vacuum at a distance scale of $1/\Lambda_{QCD}$.

In this paper, we calculate the hadronic production cross sections of T^1_{cc}, T^i_{bc} $(i = 0, 1)$, and T^1_{bb} via the gluon–gluon fusion process at LHC. Our results show that a number of these particles can be produced. We also give the signatures to detect those particles.

The rest of the paper is organized as follows. In Section 2, we present the calculation of the subprocess $gg \to T^i_{Q_1Q_2}\bar{Q}_1\bar{Q}_2 + X$. Section 3 is devoted to the numerical results of the cross sections of the tetraquark states at LHC and at Tevatron. In Section 4, we discuss the results and the signals in the detectors.

2. Cross section of $gg \to T^i_{Q_1Q_2}\bar{Q}_1\bar{Q}_2 + X$

As mentioned above, in the production process of the tetraquark states $T^i_{Q_1Q_2}$, there are three hierarchical distance scales, i.e., $1/m \ll 1/mv \ll 1/\Lambda_{QCD}$. Accordingly, the cross sections of the subprocesses for the production of the S-wave tetraquark states, $T^i_{Q_1Q_2}$, can be factored into three different parts to account for physical effects occurring at those distinct distance scales:

$$\widehat{\sigma}\left(gg \to T^i_{Q_1Q_2}\right) = \frac{1}{2\hat{s}}\frac{1}{64d}\int d\Pi_3\, C_{\bar{3}}(\alpha_s, Q_1Q_2)\left|\Psi_{\bar{3}}(0)\right|^2 \times \int_0^1 dx\, D_{\bar{3}\to T^i_{Q_1Q_2}}(x), \quad (1)$$

where $d = 1$ for T^0_{bc} and T^1_{bc}, and $d = 2$ for T^1_{bb} and T^1_{cc}; $\hat{s}$ is the squared invariant mass of the double gluons; $d\Pi_3$ is the Lorentz invariant three-body phase space integral element; $C_{\bar{3}}(\alpha_s, Q_1Q_2)$ is the short-distance coefficient describing the production rate of the color anti-triplet point-like Q_1Q_2 state at the energy scale m or higher; $\Psi_{\bar{3}}(0)$ is the wave function at the origin of the S-wave diquark state; and $D_{\bar{3}\to T^i_{Q_1Q_2}}(x)$ is the fragmentation function of the diquark into the color-singlet tetraquark state $T^i_{Q_1Q_2}$.

The short-distance coefficient can be calculated by perturbative QCD and can be expanded in terms of α_s at the short-distance energy scale m or higher. The rest parts are non-perturbative effects in nature. To estimate the production cross sections, one needs to determine their numerical values. The formation of the diquark cluster from the free double heavy quarks is described by the wave function at the origin. Their numerical values can be estimated by the potential model. The diquark cluster provides an anti-triplet color source as a heavy antiquark. Thus, in the heavy quark limit, its fragmentation probability for forming the tetraquark states can then be approximately described by that for forming the heavy baryons by a heavy quark.

In this paper, we calculate the cross sections of the hadronic production of the S-wave states, T^1_{cc}, T^1_{bc}, T^0_{bc}, and T^1_{bb}, at LHC. We compute the tree level short-distance coefficients $C_{\bar{3}}(\alpha_s, Q_1Q_2)$ in the leading order α_s^4 using perturbation QCD. By estimating the nonperturbative matrix elements, we carry out the numerical calculations of the total cross sections. Our results show that a number of these particles can be produced.

We first calculate the short-distance coefficients $C_{\bar{3}}(\alpha_s, Q_1Q_2)$ at the tree level. They are proportional to the square of the matrix elements $M(gg \to (Q_1Q_2)_{\bar{3}})$. To calculate the matrix elements, we must calculate the subprocess of $gg \to Q_1Q_2\bar{Q}_1\bar{Q}_2$, with Q_1 and Q_2 moving with the same 3-velocity and in the color anti-triplet state. At the tree level, the production processes involve 36 Feynman diagrams for $gg \to bc\bar{b}\bar{c}$, and 72 Feynman diagrams for $gg \to bb\bar{b}\bar{b}$ and $gg \to cc\bar{c}\bar{c}$. The amplitudes can be classified as six gauge-invariant subsets in terms of six independent color bases. Therefore, the calculations of the amplitudes and their squares are straightforward.

$\Psi_{\bar{3}}(0)$'s are the wave functions at the origin of the S-wave diquark clusters. Their precise values are difficult to determine because the large range interaction potential between the double heavy quarks in the color anti-triplet state is not very clear, while the short range one is dominated by the Coulomb potential. Reasonably, we take these values predicted by solving Schödinger equation with the Coulomb potential, $v(r) = -2\alpha_s/(3r)$. Then, the predicted $|\Psi_{\bar{3}}(0)|^2$'s are 0.143, 0.0382, and 0.0198 GeV^3 for bb, bc, and cc diquark systems, respectively. Including the confinement part, the wave function is squeezed to the central region, and hence the wave function at the origin is enhanced. Actually, we have performed numerical calculations for the diquark state by solving the Schrödinger equation using Coulomb potential plus the linear potential fixed in the color-singlet case, and the numerical value of the wave function at the origin is enhanced by 10%–30%. A more reliable prediction for this nonperturbative number can be obtained by a nonperturbative method such as lattice QCD.

We now turn to the fragmentation function of the $(Q_1Q_2)_{\bar{3}}$-cluster to a tetraquark state. As discussed above, the heavy diquark cluster in the color anti-triplet state provides the same color source as the heavy antiquark to the light antiquarks in the limit of the ratio of the size of the diquark over that of the light antiquarks in the tetraquark state. Thus, the fragmentation probabilities to produce the tetraquark states $T^i_{Q_1Q_2}$ from the heavy diquarks are the same as that to produce the heavy baryons from the heavy quarks. Let us take a QED example to illustrate it. Imagine a hydrogen ion or deuterium ion passing through a material. The probabilities forming the hydrogen atom or the deuterium atom are the same if the velocities of both ions are the same because they possess the same electric charge. The fragmentation function is defined in the framework of infinite momentum where the parton moves at the speed of light.

The fragmentation functions to produce the tetraquark states are nonperturbative in nature. Thus, their shapes can only be described by certain phenomenological models [7,8]. One of the most commonly used models is the Peterson model [7], in which the fragmentation function takes the following form:

$$D_{\bar{3}} \to T^i_{Q_1Q_2}(x) = \frac{N}{x[1 - (1/x) - \epsilon_{Q_1Q_2}/(1-x)]^2} \quad (2)$$

where $\epsilon_{Q_1Q_2}$ is the only parameter determining the shape of the fragmentation function and N is the normalization constant. Once the fragmentation probability to produce the tetraquark state is given, N is fixed by the following condition:

$$\int dx\, D_{\bar{3}} \to T^i_{Q_1Q_2}(x) = R. \quad (3)$$

The fragmentation probabilities of $c \to \Lambda_c$ and $b \to \Lambda_b$ have been measured in e^+e^- collisions [9–11]. According to PDG 2006 [9], $R(c \to \Lambda_c) = 0.094 \pm 0.035$, and $R(b \to \Lambda_b) = 0.099 \pm 0.017$. These results are approximately 0.1. Therefore, as a good approximation, we may take the fragmentation probability of $(Q_1Q_2)_{\bar{3}} \to T^i_{Q_1Q_2}$, the value of R in Eq. (3), to be 0.1.

From Eqs. (2) and (3), we know that the normalization constant N in the Peterson model is dependent on the parameter ϵ_Q. The model suggests a scaling behavior for the parameter ϵ_Q that is proportional to $1/m_Q^2$. The ϵ_b determined by experiments is approximately $0.003 \sim 0.006$ [10,12]. Using the scaling behavior and taking ϵ_b to be 0.004, we predict that $\epsilon_{bc} = (\frac{m_b}{m_{bc}})^2\epsilon_b \simeq 0.0023$, $\epsilon_{cc} = (\frac{m_b}{m_{cc}})^2\epsilon_b \simeq 0.011$, $\epsilon_{bb} = (\frac{m_b}{m_{bb}})^2\epsilon_b = 0.001$ and the corre-