Discovery potential of stable and near-threshold doubly heavy tetraquarks at the LHC

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We study the LHC discovery potential of the double-bottom tetraquarks $bb\bar{u}d$, $bb\bar{s}s$ and $bb\bar{d}d$, the lightest of which having $J^P = 1^+$, called $T_{bb\bar{u}d}^{(bb)}$, $T_{bb\bar{s}s}^{(bb)}$ and $T_{bb\bar{d}d}^{(bb)}$, are expected to be stable against strong decays. Employing the Monte Carlo generators MadGraph5_aMC@NLO and Pythia6, we simulate the process $pp \to bbbb + X$ and calculate the $bb$-diquark jet configurations, specified by the invariant mass interval $M_{ab} < M_{T_{bb\bar{u}d}^{(bb)}}, M_{T_{bb\bar{s}s}^{(bb)}}, M_{T_{bb\bar{d}d}^{(bb)}}$, are presented and used to get the $bb$-diquark jet cross sections in double-bottom hadrons $(pp \to H_{bb\bar{u}d} + X)$, where $H_{bb\bar{u}d}$ represent tetraquarks and baryons. This is combined with the LHCb data on the fragmentation $b \to A_b$ and $b \to B$ to obtain $\sigma(pp \to T_{bb\bar{u}d}^{(bb)} + X) = (2.8^{+1.0}_{-0.7})$ nb at $\sqrt{s} = 13$ TeV, and about a quarter of this for the $T_{bb\bar{s}s}^{(bb)}$ and $T_{bb\bar{d}d}^{(bb)}$, each. We also present estimates of the production cross sections for the mixed bottom-charm tetraquarks, $bc\bar{u}d$, $bc\bar{s}s$ and $bc\bar{d}d$, obtaining $\sigma(pp \to T_{bc\bar{u}d}^{(bc)} + X) = (103^{+39}_{-25})$ nb at $\sqrt{s} = 13$ TeV, and the related ones having $T_{bc\bar{s}s}^{(bc)}$ and $T_{bc\bar{d}d}^{(bc)}$. They have excellent discovery potential at the LHC, as their branching ratios in various charge combinations of $BD_{ij}(\gamma)$ are anticipated to be large. © 2018 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP3.

I n t r o d u c t i o n: The discovery of $X(3872)$, followed by well over a dozen related mesonic states, $X$, $Y$, $Z$, and two baryonic states $P_c$(4380) and $P_c$(4450), has opened a second layer of “extraordinary” hadrons in QCD, containing four and five valence quarks and antiquarks [1]. However, their dynamics is not yet deciphered and is under intense study. The competing theoretical models put forward can be roughly classified into two categories: those reflecting the residual QCD long-distance effects, dominated by meson exchanges, and those reflecting genuine short-distance interactions, dominated by gluon exchanges. Their spectroscopy, production and decay characteristics are discussed in a number of reviews [2–6]. Based on the experimental observation of doubly-charmed baryons [7] and Heavy Quark Symmetry (HQS), recent theoretical insights have brought new perspectives, implying that doubly-heavy tetraquarks (DHTQ) $Q_i Q_j \bar{q}_k \bar{q}_l$ must exist in the HQS limit. Here $Q_i$, $Q_j$ are either $b$ or $c$ quarks, and $\bar{q}_k$, $\bar{q}_l$ are light ($u$, $d$, $s$) antiquarks. The existence of such tetraquarks was already suggested in the earlier works [8,9], but this argument has received a great impetus from proofs based on HQS and lattice-QCD [10–16]. In particular, HQS relates the DHTQ masses to those of double-heavy baryons, heavy-light baryons, and heavy-light mesons. As the light degrees of freedom in these hadrons are similar, we anticipate that the heavy quark–heavy diquark symmetry has implications for other non-perturbative aspects as well. In particular, this symmetry can be used as a quantitative guide in the analysis of the current and anticipated experiments.

The lightest of the $bb\bar{u}d$, $bb\bar{s}s$, and $bb\bar{d}d$ states are anticipated to be stable against strong decays. Heavier $bb\bar{q}_k \bar{q}_l$ states, as well as the double-charm states $cc\bar{q}_k \bar{q}_l$, and the mixed bottom-charm tetraquark states $bc\bar{q}_k \bar{q}_l$, on the other hand, are estimated to have masses above their respective thresholds. The latter are likely to dissociate into pairs of heavy-light mesons, with large branching ratios, some of which may appear as “double-flavor” narrow...
resonances [10,11,17,18]. None of these stable or near-threshold DHTQ mesons has so far been seen experimentally. Observing them would establish the existence of tetraquarks, underscoring the role of diquarks, with well-defined colour and spin quantum numbers [19–21], as fundamental constituents of hadronic matter.

Our main focus is to develop the expectations for the production of some of the DHTQ mesons, in particular, the double-bottom $J^P = 1^+$ tetraquarks $T^{(bb)}_{[dd]}$, and the related ones $T^{(bb)}_{[uu]}$ and $T^{(bb)}_{[uu]}$. The standard calculational technique, NRQCD and related frameworks [22], however, can not be used at present, as the hadronic matrix elements required for tetraquark production are unknown. The DHTQ decay products are expected to lie in well-collimated double-heavy-diquark jets, which are formed in high energy collisions. These configurations can be calculated in perturbative QCD and, combined with non-perturbative (fragmentation) aspects measured in $b$-quark jets, enable us to estimate the cross sections of interest.

In a previous paper [23], we have studied the production of double-bottom tetraquarks at a Tera-Z factory in $e^+e^-$ collision, employing the $bb$-diquark jet configurations in which such tetraquarks are likely to be produced. In this Letter, we study the production of DHTQ states at the LHC, making use of the impressive LHCb data on $pp \rightarrow B_c + X$ [24] and $b$-hadron production fractions in $pp$ collisions [25,26]. Also, double-bottomonium production has been observed at the LHC, with CMS reporting a cross section $\sigma(pp \rightarrow \Upsilon(1S) \Upsilon(1S) + X) = 68 \pm 15$ pb at $\sqrt{s} = 8$ TeV [27]. This is the first step in the searches of double-bottom-tetraquarks, such as $pp \rightarrow T^{(bb)}_{[dd]} + X$, as both final states involve different fragmentation of the same underlying partonic process $pp \rightarrow b\bar{b}c + X$. Using the Monte Carlo generators MadGraph5 _aMC@NLO [28] and Pythia8 [29], we simulate the process $pp \rightarrow b\bar{b}c + X$ and estimate that the production cross section $\sigma(pp \rightarrow T^{(bb)}_{[dd]} + X)$ can reach a few nb. Replacing a bottom quark by a charm quark, we also simulate the process $pp \rightarrow b\bar{b}c + X$ and calculate the production of the mixed bottom-charm tetraquarks $T^{(bc)}_{[cc]}$, $T^{(bc)}_{[cc]}$, and $T^{(bc)}_{[cc]}$, having $J^P = 0^+$, and their $J^P = 1^+$ partners, which are estimated to lie above their corresponding heavy-light mesonic thresholds. We find that the cross sections for these tetraquarks may reach $O(50)$ nb. As LHCb is projected to collect an integrated luminosity of 50 fb$^{-1}$ in Runs 1–4 [30–32], the prospects of discovering these tetraquarks are excellent.

Production of double-bottom tetraquarks at the LHC: We start by recalling the production and decays of the known doubly-heavy meson $B_{c}^{\pm}$ in the process $pp \rightarrow b\bar{b}c + X \rightarrow B_{c}^{\pm} + X$, which serves as the benchmark for our calculations. At $\sqrt{s} = 8$ TeV, the LHCb collaboration has measured the ratio [24]$\dagger$

$$R \equiv \frac{\sigma(B_{c}^{+})}{\sigma(B_{c}^{+})} \frac{B(B_{c}^{+} \rightarrow J/\psi \pi^+)}{B(B_{c}^{+} \rightarrow J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%,$$

where $0 < p_T < 20$ GeV, and $2.0 < y < 4.5$, with $p_T$ and $y$ being the component of the momentum transverse to the proton beam and rapidity, respectively.

This value is consistent with the previous LHCb measurement [33]. At $\sqrt{s} = 7$ TeV, the $B^+$ production cross section is measured as [34]

$$\sigma(B^+) = (43.0 \pm 0.2 \pm 2.5 \pm 1.7) \mu b,$$  

$\dagger$ Throughout this Letter, charge conjugation is assumed.

with the same kinematics. Using MadGraph [28] and Pythia [29], we find that the 8 TeV cross section is expected to be enhanced by about 19%, compared with the 7 TeV cross section, which is consistent with 20% used in [24]. Using the above results, and the branching ratio [1]

$$B(B_{c}^{+} \rightarrow J/\psi K^+) = (1.026 \pm 0.031) \times 10^{-3},$$  

we find:

$$\sigma(B_{c}^{+}) B(B_{c}^{+} \rightarrow J/\psi \pi^+) = (0.36 \pm 0.03) \text{ nb}.$$  

To extract the cross section from the above product, we need to know $B(B_{c}^{+} \rightarrow J/\psi \pi^+)$, which is, in general, model-dependent. Noting that there is considerable spread in the predicted value of this quantity in the literature, we use two calculations of the more recent vintage, which we consider more reliable, based on the perturbative QCD approach (pQCD) [35], and on the NLO non-relativistic QCD (NRQCD) [36], which yield:

$$B(B_{c}^{+} \rightarrow J/\psi \pi^+) = (2.6^{+0.6-0.2}_{-0.4-0.2}) \times 10^{-3} \text{ (pQCD)},$$  

$$B(B_{c}^{+} \rightarrow J/\psi \pi^+) = (2.91^{+0.15+0.42}_{-0.42-0.23}) \times 10^{-3} \text{ (NRQCD)}.$$  

With this, the production cross section $\sigma(pp \rightarrow B_{c}^{+} + X)$ at $\sqrt{s} = 8$ TeV is estimated as:

$$\sigma(pp \rightarrow B_{c}^{+} + X) = (139^{+34}_{-41}) \text{ nb (pQCD)},$$  

$$\sigma(pp \rightarrow B_{c}^{+} + X) = (124^{+28}_{-19}) \text{ nb (NRQCD)}.$$  

The implicit model-dependence can be checked by using the ratios of the semileptonic decays of the $B_{c}^{+}$ and $B^{\pm}$, which have a much larger statistics.

Next, we use MadGraph [28] to calculate the cross section for the process $pp \rightarrow b\bar{b}c + X$ at $\sqrt{s} = 8$ TeV, which yields

$$\sigma(pp \rightarrow b\bar{b}c + X) = (4.79 \pm 0.08) \times 10^{3} \text{ nb}.$$  

As the quarks involved are heavy, charm or bottom, their masses regulate the infrared singularity, which would be present for the massless quarks. Hence, at the generation level in our simulations, there are no partonic cuts, i.e., in the gluon fusion $gg \rightarrow b\bar{b}c$ and annihilation of the light quark and antiquark $q\bar{q} \rightarrow b\bar{b}c$. This determines for us the fragmentation fraction:

$$f(c\bar{b} \rightarrow B_{c}^{+}) = (2.5^{+0.7}_{-0.6}) \text{ (pQCD)},$$  

$$f(c\bar{b} \rightarrow B_{c}^{+}) = (2.6^{+0.5}_{-0.3}) \text{ (NRQCD)}.$$  

Here, the $B_{c}^{+}$ mesons survive the cuts $p_T < 20$ GeV and $2.0 < y < 4.5$. For the fragmentation to take place, both the $b$ and the $c$ quarks have to be collinear in a well-collimated jet, defined by an invariant mass interval $\Delta M$. The fragmentation products include also the excited states of $B_{c}^{+}$, which feed to inclusive $B_{c}^{+}$ production through subsequent decays. We estimate the value of $\Delta M$ so as to reproduce the above fragmentation ratio. This yields:

$$\Delta M = (2.0^{+0.5}_{-0.4}) \text{ GeV (pQCD)},$$  

$$\Delta M = (1.9^{+0.3}_{-0.3}) \text{ GeV (NRQCD)},$$  

which is consistent with $\Delta M = (2.2 - 4.0)$ GeV that we obtained from simulating the $Z$ decays in [23], using NRQCD for $\sigma(e^+e^- \rightarrow B_c + X)$ [37], but more precise. The method of $\Delta M$

$^2$ With the cuts $0 < p_T < 20$ GeV, and $2.0 < y < 4.5$ and setting $m_0 = 4.9$ GeV, we find that the $b\bar{b}$ cross sections at the 7 and 8 TeV LHC are about 80 μb and 95 μb, respectively. This ratio is less sensitive to the hadronization.
determination used here is, however, on a firmer footing as the experimental measurement of $\sigma(B_{s}^{+}) \times B(B_{s}^{+} \to J/\psi \pi^{+})$ by LHCb, together with the perturbative QCD estimates of the cross section $\sigma(pp \to b \bar{b} c \bar{c} + X)$, provides the normalization for the inclusive fragmentation $f(c\bar{b} \to B_{s}^{+})$.

For $pp \to bbb + X$, we have generated $10^{5}$ showered events at $\sqrt{s} = 13$ TeV with MadGraph [26] and Pythia6 [27] at the NLO accuracy. The cross section $\sigma(pp \to bbb + X)$, involving the gg and q\bar{q} partons, is evaluated by MadGraph to be $(463 \pm 4)$ nb. We also find that the contribution from the Z-induced processes, $(pp \to Z + X \to bbb + X)$ and $(pp \to Zbb + X \to bbb + X)$, is down by three orders of magnitude, and hence is not considered any further.

The $b$-quark pair invariant mass distribution is displayed in Fig. 1. We compare the normalized $b$-quark invariant mass distribution at the LHC ($\sqrt{s} = 13$ TeV) with the corresponding one in $e^{+}e^{-}$ collision at the Z pole in Fig. 2, upper panel, while the lower panel shows the ratio of the two. From this figure, we see that the jet-shapes (normalized distributions) are similar in the two cases in the small invariant mass region. Thus, the same jet-resolution criteria can be used in the two processes to estimate the fraction of the $bb$-invariant mass in which the $bb$-diquark is likely to fragment into double-bottom hadrons. We use $\Delta M = 2.0^{+0.3}_{-0.4}$ GeV, obtained from the analysis of the data on $\sigma(pp \to B_{s}^{+} + X)$ at $\sqrt{s} = 8$ TeV, discussed earlier, which yields the following fragmentation fraction and the corresponding cross section

$$f(bb \to H_{[bb]} = (3.2^{+1.2}_{-0.8})\%,$$

(10)

$$\sigma(pp \to H_{[bb]} + X) = (14.8^{+5.4}_{-3.7}) \text{ nb.}$$

(11)

The double-bottom hadrons $H_{[bb]}$ include the double-heavy tetraquarks $T_{[bb]}^{(0)}$ and the double-bottom baryons $X_{bb}^{0}(bbu)$, $X_{bb}^{0}(bbd)$, and $\Omega_{bb}^{0}(bb)$, and their excited states, as well as some non-resonant open-bottom background, such as $BB^{(*)} + X$, which we expect to be small due to the stringent $\Delta M$ cut. The relative fractions of $H_{[bb]} \to T_{[bb]}^{(0)} + H_{[bb]} \to X_{bb}^{0}(bbu)$, $X_{bb}^{0}(bbd)$, $\Omega_{bb}^{0}(bb)$ are not known. In the fragmentation language, they involve the vacuum excitation of a light anti-diquark pair $(\tilde{q}\tilde{q}')$ in the former, and of a light quark–antiquark pair in the latter. We assume, appealing to the heavy quark–heavy diquark symmetry, that they are similar to the measured ones in a single $b$-quark jet, for which LHCb has reported the following $p_{T}$-dependent ratio [25]:

$$\left[ \frac{f_{bb} + f_{f \bar{f}}}{f_{bb}} \right] \left( p_{T} \right) = (0.404 \pm 0.036) \times \left[ 1 - (0.031 \pm 0.005) p_{T}(\text{GeV}) \right],$$

(12)

where we have added in quadrature the various errors quoted in [25]. To use this input, we need to first calculate the $p_{T}$-distribution of the $bb$-diquark jet in $pp \to (bb)_{jet} + b + \bar{b} + X$. This is shown in Fig. 3, where the $(bb)_{jet}$ is defined by the interval $\Delta M_{bb}(\Delta M)$ with $\Delta M = 2.0$ GeV.

We convolute this distribution with the one measured by LHCb for $\left[ \frac{f_{bb} + f_{f \bar{f}}}{f_{bb}} \right] \left( p_{T} \right)$, given above, and estimate the ratio of the $T_{[bb]}^{(0)}$ production cross section to the $H_{[bb]}$ production cross section:

$$\frac{\sigma(pp \to T_{[bb]}^{(0)} + X)}{\sigma(pp \to H_{[bb]} + X)} = 0.195 \pm 0.014,$$

(13)

with both $H_{[bb]}$ and $T_{[bb]}^{(0)}$ having $p_{T} < 20$ GeV. Here, we have assumed that the final state $H_{[bb]} + X$ is saturated by the double-bottom baryons and double-bottom tetraquarks, and the ratio of the production rates of the strange and non-strange $B$ mesons, $f_{s}/f_{d} = 0.256 \pm 0.020$ measured by the LHCb collaboration [38], also holds in the fragmentation of a $bb$ jet. This leads finally to the integrated cross section:


The production cross section for the doubly-bottom tetraquarks (summed over the states) are estimated as

\[
\sigma(pp \rightarrow T_{[ud]}^{[bb]} + X) : \sigma(pp \rightarrow \Upsilon_{[ud]}^{[bb]} + X) \approx 2.4. \tag{15}
\]

Thus, we anticipate about twice as many doubly-bottom baryons as the double-bottom tetraquarks at the 13 TeV LHC.

The LHCb collaboration is expected to collect about 50 fb⁻¹ of data in Runs 1–4 [30–32], which would translate into \(O(10^8)\) \(T_{[ud]}^{[bb]}\) events. Taking into account the \(sS\)-suppression, compared to \(dd\) or \(uu\), we expect approximately a quarter of this number for the other two doubly-bottom tetraquarks \(T_{[ud]}^{[bb]}\) and \(T_{[ud]}^{[bb]}\), each. Their lifetimes are expected to be very similar, and estimated as 0.8 ps [23]. Their anticipated discovery modes have typical branching ratios of \(O(10^{-5})\) [23,39], much smaller than the one for decays of doubly charmed baryons \[40,41\] which are recently observed by LHCb [7]. It indicates that dedicated searches at the LHC will be required to discover them.

**Production of \(T_{[ud]}^{[bc]}\) at the LHC:** As already noted, LHCb has collected an impressive amount of \(B_c\) events, with \(2.1 \times 10^3\) \(B_c \rightarrow J/\psi \pi\) candidates in 2 fb⁻¹ pp collisions at 8 TeV [24]. As the underlying partonic process is the same for the tetraquark \(T_{[ud]}^{[bc]}\) production, but non-perturbative aspects differ, we evaluate the production cross section \(\sigma(pp \rightarrow \Upsilon_{[ud]}^{[bc]} + X)\). For that we generate 10⁴ showered \(pp \rightarrow bb\) events at the pp centre-of-mass energy 8 TeV, using the generators MadGraph [28] and Pythia6 [29] at the NLO accuracy. The cross section \(\sigma(pp \rightarrow bb\) + X) is evaluated by MadGraph to be \((4.79 \pm 0.08)\) fb, which on using M = (2.010⁻⁵) GeV yields the following fragmentation fraction and the corresponding cross section:

\[
f(bb \rightarrow H_{[bc]} = (5.7_{-2.4}^{+2.4})\%.
\]

\[
\sigma(pp \rightarrow H_{[bc]} + X) = (273_{-13}^{+11})\text{ nb}. \tag{16}
\]

Combined with Eq. (12) for the fragmentation fraction, we get at \(\sqrt{s} = 8\) TeV

\[
\sigma(pp \rightarrow \Upsilon_{[ud]}^{[bc]} + X) = (57_{-22}^{+22})\text{ nb}, \tag{17}
\]

with \(p_T(T_{[ud]}^{[bc]}) < 20\text{ GeV}.\) This cross section is larger than an earlier estimate [42], in which the diquark with heavy quarks is first produced and then fragment into the tetraquark state. Assuming a detection efficiency of \(10^{-6}\), we anticipate \(O(10^3)\) \(T_{[ud]}^{[bc]}\) candidate events in the currently available LHCb data set, and approximately a quarter of this number for the related tetraquarks \(T_{[ad]}^{[bc]}\) and \(T_{[dd]}^{[bc]}\). There is considerable uncertainty in these estimates as the mixed bottom-charm tetraquarks, as opposed to the stable \(bb\)-tetraquarks, have \(J^P = 0^+\) and \(J^P = 1^+\), and their relative production rates in the fragmentation of a \(cb\)-diquark is an additional unknown parameter. They apply to the sum of both the \(J^P\) states. The mass of \(T_{[ad]}^{[bc]}\) is estimated in Ref. [11] to be \(7229\) MeV, some \(83\) MeV above the \(BD\) threshold, and one expects a narrow resonance in this channel. The masses of the other two tetraquarks with \(s\)-quark, are pitched at \(7406\) MeV, some \(170\) MeV above the \(B_sD\) threshold [11], considerably broadening the resonances.

Finally, the cross section \(\sigma(pp \rightarrow bb\) + \(X̄_{[bc]} + X)\) at 13 TeV is evaluated by MadGraph to be \((8.76 \pm 0.19)\) fb. Repeating the steps indicated for the 8 TeV case, we estimate that

\[
\sigma(pp \rightarrow \Upsilon_{[ad]}^{[bc]} + X) = (103_{-25}^{+39})\text{ nb}. \tag{19}
\]

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