

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

Ahmed Ali,<sup>1,\*</sup> Qin Qin,<sup>2,†</sup> and Wei Wang<sup>3,‡</sup>

<sup>1</sup>*Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg, Germany*

<sup>2</sup>*Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät,  
Universität Siegen, Walter-Flex-Strasse 3, D-57068 Siegen, Germany*

<sup>3</sup>*INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology,  
MOE Key Laboratory for Particle Physics, School of Physics and Astronomy,  
Shanghai Jiao Tong University, Shanghai 200240, China*

(Dated: June 26, 2018)

We study the LHC discovery potential of the double-bottom tetraquarks  $bb\bar{u}\bar{d}$ ,  $bb\bar{u}\bar{s}$  and  $bb\bar{d}\bar{s}$ , the lightest of which having  $J^P = 1^+$ , called  $T_{[\bar{u}\bar{d}]}^{\{bb\}}$ ,  $T_{[\bar{u}\bar{s}]}^{\{bb\}}$  and  $T_{[\bar{d}\bar{s}]}^{\{bb\}}$ , are expected to be stable against strong decays. Employing the Monte Carlo generators MadGraph5\_aMC@NLO and Pythia6, we simulate the process  $pp \rightarrow bb\bar{b}\bar{b}$  and calculate the  $bb$ -diquark jet configurations, specified by the invariant mass interval  $m_{bb} < M_{T_{[q\bar{q}]}}^{\{bb\}} + \Delta M$ . Estimates of  $\Delta M$  from the measured product

$\sigma(pp \rightarrow B_c^+ + X)\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$  are presented and used to get the  $bb$ -diquark jet cross sections in double-bottom hadrons  $\sigma(pp \rightarrow H_{\{bb\}} + X)$ , where  $H_{\{bb\}}$  represent tetraquarks and baryons. This is combined with the LHCb data on the fragmentation  $b \rightarrow \Lambda_b$  and  $b \rightarrow B$  to obtain  $\sigma(pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + X) = (2.4_{-0.6}^{+0.9})$  nb, and about a half of this for the  $T_{[\bar{u}\bar{s}]}^{\{bb\}}$  and  $T_{[\bar{d}\bar{s}]}^{\{bb\}}$ . We also present estimates of the production cross sections for the mixed bottom-charm tetraquarks,  $bc\bar{u}\bar{d}$ ,  $bc\bar{u}\bar{s}$  and  $bc\bar{d}\bar{s}$ , obtaining  $\sigma(pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bc\}} + X) = (48_{-12}^{+19})$  nb, and the related ones having  $T_{[\bar{u}\bar{s}]}^{\{bc\}}$  and  $T_{[\bar{d}\bar{s}]}^{\{bc\}}$ . They have excellent discovery potential at the LHC, as their branching ratios in various charge combinations of  $BD_{(s)}(\gamma)$  are anticipated to be large.

PACS numbers:

*Introduction:* 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].

Recent theoretical insights, based on heavy quark symmetry (HQS), have brought new perspectives, implying that doubly-heavy tetraquarks (DHTQ)  $Q_i Q_j \bar{q}_k \bar{q}_\ell$  must exist in the HQS limit. Here  $Q_i, Q_j$  are either  $b$  or  $c$  quarks, and  $\bar{q}_k, \bar{q}_\ell$  are light ( $\bar{u}, \bar{d}, \bar{s}$ ) antiquarks. The existence of such tetraquarks was already suggested in the earlier works [7, 8], but this argument has received a great impetus from proofs based on HQS and lattice-QCD [9–15]. 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 data.

The lightest of the  $bb\bar{u}\bar{d}$ ,  $bb\bar{u}\bar{s}$ , and  $bb\bar{d}\bar{s}$  states are anticipated to be stable against strong decays. Heavier  $bb\bar{q}_k\bar{q}_\ell$  states, as well as the double-charm states  $cc\bar{q}_k\bar{q}_\ell$ , and the mixed bottom-charm tetraquark states  $bc\bar{q}_k\bar{q}_\ell$ , 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 [9, 10, 16, 17]. 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 color and spin quantum numbers [18–20], as fundamental constituents of hadronic matter.

Our main focus is to develop the expectations about the production of some of the DHTQ mesons., in particular, the double-bottom  $J^P = 1^+$  tetraquarks  $T_{[\bar{u}\bar{d}]}^{\{bb\}}$ , and the related ones  $T_{[\bar{u}\bar{s}]}^{\{bb\}}$  and  $T_{[\bar{d}\bar{s}]}^{\{bb\}}$ . The standard calculational technique, NRQCD and related frameworks [21], however, can not be used at present, as the hadronic ma-

trix 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 [22], 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  $pp \rightarrow B_c + X$  [23] and  $b$ -hadron production fractions in pp collisions [24, 25]. 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 [26]. This is the first step in the searches of double-bottom tetraquarks, such as  $pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + X$ , as both final states involve different fragmentation of the same underlying partonic process  $pp \rightarrow b\bar{b}b\bar{b}$ . Using the Monte Carlo generators MadGraph5\_aMC@NLO [27] and Pythia6 [28], we simulate the process  $pp \rightarrow b\bar{b}b\bar{b}$  and estimate that the production cross section  $\sigma(pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + X)$  can reach a few nb. Replacing a heavy bottom quark by a charm quark, we also simulate the process  $pp \rightarrow b\bar{b}c\bar{c}$  and calculate the production of the mixed bottom-charm tetraquarks  $T_{[\bar{u}\bar{d}]}^{[bc]}$ ,  $T_{[\bar{u}\bar{s}]}^{[bc]}$  and  $T_{[\bar{d}\bar{s}]}^{[bc]}$ , 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  $\mathcal{O}(50)$ nb. As LHCb is projected to collect an integrated luminosity of  $50 \text{ fb}^{-1}$  in Runs 1-4 [29–31], 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  $pp \rightarrow b\bar{b}c\bar{c} \rightarrow B_c^\pm + X$ , which serves as the benchmark for our calculations. At  $\sqrt{s} = 8$  TeV, the LHCb collaboration has measured the ratio [23]<sup>1</sup>

$$R \equiv \frac{\sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \mathcal{B}(B^+ \rightarrow J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%, \quad (1)$$

where  $0 < p_T < 20$  GeV, and  $2.0 < y < 4.5$ . This value is consistent with the previous LHCb measurement [32]. At  $\sqrt{s} = 7$  TeV, the  $B^+$  production cross section is measured

as [33]

$$\sigma(B^+) = (43.0 \pm 0.2 \pm 2.5 \pm 1.7) \mu\text{b}, \quad (2)$$

with the same kinematic cuts. Using MadGraph [27] and Pythia [28], we find that the 8 TeV cross section is expected to be enhanced by about 19%, compared with the 7 TeV cross section,<sup>2</sup> which is consistent with 20% used in [23]. Using the above results, and the branching ratio [1]

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

we find:

$$\sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) = (0.36 \pm 0.03) \text{ nb}. \quad (4)$$

To extract the cross section from the above product, we need to know  $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$ , 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) [34], and on the NLO non-relativistic QCD (NRQCD) [35], which yield:

$$\begin{aligned} \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) &= (2.6_{-0.4}^{+0.6+0.2+0.8}) \times 10^{-3} \text{ (PQCD)}, \\ \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) &= (2.91_{-0.42}^{+0.15+0.40}) \times 10^{-3} \text{ (NRQCD)}. \end{aligned} \quad (5)$$

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

$$\begin{aligned} \sigma(pp \rightarrow B_c^+ X) &= (139_{-41}^{+34}) \text{ nb (PQCD)}, \\ \sigma(pp \rightarrow B_c^+ X) &= (124_{-19}^{+28}) \text{ nb (NRQCD)}. \end{aligned} \quad (6)$$

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

Next, we use Madgraph [27] to calculate the cross section for the process  $pp \rightarrow b\bar{b}c\bar{c}$  at  $\sqrt{s} = 8$  TeV, which yields

$$\sigma(pp \rightarrow b\bar{b}c\bar{c}) = (4.79 \pm 0.08) \times 10^3 \text{ nb}. \quad (7)$$

This determines for us the fragmentation fraction:

$$\begin{aligned} f(b\bar{c} \rightarrow B_c^+) &= (2.9_{-0.8}^{+0.7})\% \text{ (PQCD)}, \\ f(b\bar{c} \rightarrow B_c^+) &= (2.6_{-0.3}^{+0.5})\% \text{ (NRQCD)}. \end{aligned} \quad (8)$$

In the above the  $B_c^+$  mesons survive the cuts  $p_T < 20$  GeV and  $2.0 < y < 4.5$ . Noting that for the fragmentation to take place, both the  $b$  and the  $\bar{c}$  quarks have to be

<sup>2</sup> With the cuts  $0 < p_T < 20$  GeV, and  $2.0 < y < 4.5$  and setting  $m_b = 4.9$  GeV, we find that the  $b\bar{b}$  cross sections at the 7 and 8 TeV LHC are about  $80 \mu\text{b}$  and  $95 \mu\text{b}$ , respectively. This ratio is less sensitive to the hadronization.

<sup>1</sup> Throughout this Letter, charge conjugation is assumed.

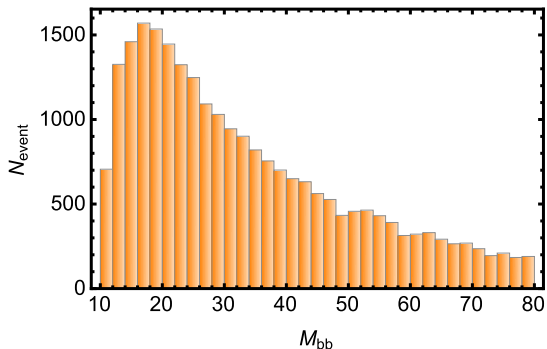


FIG. 1: The  $bb$ -quark-pair invariant-mass distribution for the process  $pp \rightarrow (bb)_{\text{jet}} + \bar{b} + \bar{b} + X$  at  $\sqrt{s} = 13$  TeV, obtained by generating  $10^5$  events using MadGraph and Pythia6 at the NLO accuracy.

collinear in a well-collimated jet, defined by an invariant mass interval  $\Delta M$ . We estimate the value of  $\Delta M$  so as to reproduce the above fragmentation ratio. This yields:

$$\begin{aligned} \Delta M &= (2.0_{-0.4}^{+0.5}) \text{ GeV (PQCD)}, \\ \Delta M &= (1.9_{-0.3}^{+0.3}) \text{ GeV (NRQCD)}, \end{aligned} \quad (9)$$

which is consistent with  $\Delta M = (2.2 - 4.0)$  GeV, which we obtained from simulating the  $Z$  decays in [22], using NRQCD for  $\sigma(e^+e^- \rightarrow B_c + X)$  [36], but more precise.

For  $pp \rightarrow b\bar{b}b\bar{b}$ , we have generated  $10^5$  showered events at  $\sqrt{s} = 13$  TeV with MadGraph [27] and Pythia6 [28] at the NLO accuracy. The cross section  $\sigma(pp \rightarrow b\bar{b}b\bar{b} + X)$ , 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, ( $pp \rightarrow Z \rightarrow b\bar{b}b\bar{b} + X$ ) and ( $pp \rightarrow Zb\bar{b} \rightarrow b\bar{b}b\bar{b} + X$ ), 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  $bb$ -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 criterion 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  $\Delta M = (2.0_{-0.4}^{+0.5})$  GeV, obtained from the analysis of the data on  $\sigma(pp \rightarrow B_c^+ + X)$  at  $\sqrt{s} = 8$  TeV, discussed earlier, which yields the following fragmentation fraction and the corresponding cross section

$$f(bb \rightarrow H_{\{bb\}}) = (3.2_{-0.8}^{+1.2})\%, \quad (10)$$

$$\sigma(pp \rightarrow H_{\{bb\}}) = (14.8_{-3.7}^{+5.4}) \text{ nb}. \quad (11)$$

The double-bottom hadrons  $H_{\{bb\}}$  include the double-heavy tetraquarks  $T_{[\bar{q}\bar{q}]}^{\{bb\}}$  and the double-bottom baryons

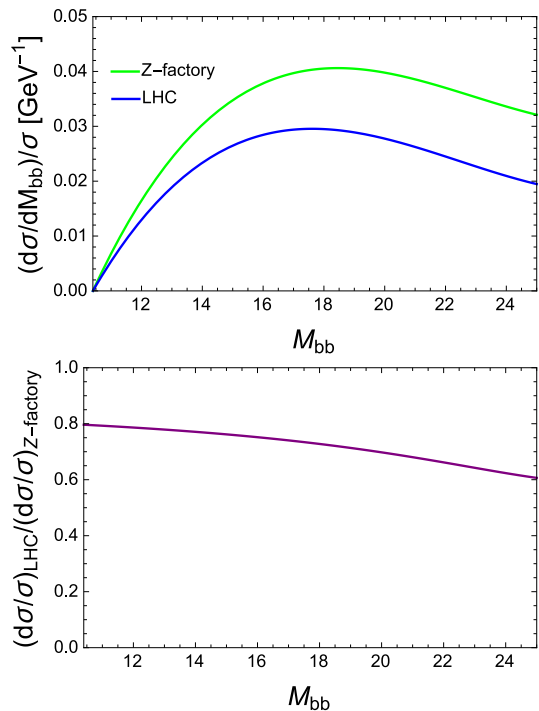


FIG. 2: Normalized differential cross section  $\frac{1}{\sigma}[d\sigma(pp \rightarrow (bb)_{\text{jet}} + \bar{b} + \bar{b} + X)/dM_{bb}]$  at the LHC (13 TeV) versus the corresponding cross section at the  $Z$  pole (upper panel) and the ratio of the normalized differential cross sections (lower panel). See text for details.

$\Xi_{bb}^0(bb\bar{u})$ ,  $\Xi_{bb}^-(bb\bar{d})$ , and  $\Omega_{bb}^-(bb\bar{s})$ . The relative fractions of  $H_{\{bb\}} \rightarrow T_{[\bar{q}\bar{q}]}^{\{bb\}}$  and  $H_{\{bb\}} \rightarrow \Xi_{bb}^0(bb\bar{u})$ ,  $\Xi_{bb}^-(bb\bar{d})$ ,  $\Omega_{bb}^-(bb\bar{s})$  are not known. In the fragmentation language, they involve the vacuum excitation of a light anti-diquark pair ( $\bar{q}\bar{q}'$ ) 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 [24]:

$$\begin{aligned} \left[ \frac{f_{\Lambda_b}}{f_{B_u} + f_{B_d}} \right] (p_T) &= (0.404 \pm 0.036) \\ &\times [1 - (0.031 \pm 0.005)p_T(\text{GeV})], \end{aligned} \quad (12)$$

where we have added in quadrature the various errors quoted in [24]. To use this input, we need to first calculate the  $p_T$ -distribution of the  $bb$ -diquark jet in  $pp \rightarrow (bb)_{\text{jet}} + \bar{b} + \bar{b} + X$ . This is shown in FIG 3, where the  $(bb)_{\text{jet}}$  is defined by the interval  $M_{bb}(\Delta M)$  with  $\Delta M = 2.0$  GeV.

We convolute this distribution with the one measured by LHCb for  $\left[ \frac{f_{\Lambda_b}}{f_{B_u} + f_{B_d}} \right] (p_T)$ , given above, and estimate the ratio of the  $T_{[\bar{u}\bar{d}]}^{\{bb\}}$  production cross section to the

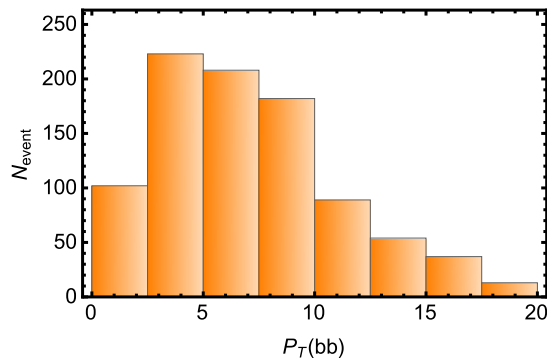


FIG. 3: The  $bb$ -quark-pair  $p_T$  distribution for the process  $pp \rightarrow (bb)_{\text{jet}} + \bar{b} + \bar{b} + X$  at  $\sqrt{s} = 13$  TeV, obtained by generating  $10^5$  events using MadGraph and Pythia6 at the NLO accuracy. The  $(bb)_{\text{jet}}$  is defined by the interval  $M_{bb}(\Delta M)$  with  $\Delta M = 2.0$  GeV.

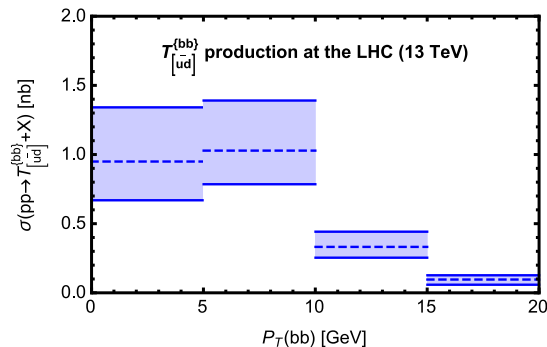


FIG. 4: Projected  $p_T$ -dependence of tetraquark production cross section in  $pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + X$  at the LHC for  $\sqrt{s} = 13$  TeV.

$H_{\{bb\}}$  production cross section:

$$\frac{\sigma(pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + X)}{\sigma(pp \rightarrow H_{\{bb\}} + X)} = 0.17 \pm 0.01, \quad (13)$$

with both  $H_{\{bb\}}$  and  $T_{[\bar{u}\bar{d}]}^{\{bb\}}$  having  $p_T < 20$  GeV. This leads finally to the integrated cross section:

$$\sigma(pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + X) = (2.4_{-0.6}^{+0.9}) \text{ nb}. \quad (14)$$

The  $p_T$ -distribution of the differential cross section for  $pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + X$  is shown in Fig. 4.

The production cross sections for the double-bottom baryons (summed over the states) are estimated as

$$\sigma(pp \rightarrow (\Xi_{bb}^0, \Xi_{bb}^-, \Omega_{bb}^-) + X) : \sigma(pp \rightarrow T_{[\bar{q}\bar{q}']}^{\{bb\}} + X) \approx 2 : 1. \quad (15)$$

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

The LHCb collaboration is expected to collect about  $50 \text{ fb}^{-1}$  of data in Runs 1-4 [29–31], which would translate into  $\mathcal{O}(10^8)$   $T_{[\bar{u}\bar{d}]}^{\{bb\}}$  events. Taking into account the  $s\bar{s}$ -suppression, compared to  $d\bar{d}$  or  $u\bar{u}$ , we expect approximately half this number for the other two doubly-bottom tetraquarks  $T_{[\bar{u}\bar{s}]}^{\{bb\}}$  and  $T_{[\bar{s}\bar{d}]}^{\{bb\}}$ . Their lifetimes are expected to be very similar, and estimated as 0.8 ps [24]. Their anticipated discovery modes [22, 37], which have typical branching ratios of  $\mathcal{O}(10^{-6})$ , suggest that dedicated searches at the LHC will be required to discover them.

*Production of  $T_{[\bar{u}\bar{d}]}^{\{bc\}}$  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  $2 \text{ fb}^{-1}$  pp collisions at 8 TeV [23]. As the underlying partonic process is the same for the tetraquark  $T_{[\bar{u}\bar{d}]}^{\{bc\}}$  production, but non-perturbative aspects differ, we evaluate the production cross section  $\sigma(pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bc\}} + X)$ . For that we generate  $10^4$  showered  $pp \rightarrow b\bar{b}c\bar{c}$  events at the  $pp$  centre-of-mass energy 8 TeV, using the generators MadGraph [27] and Pythia6 [28] at the NLO accuracy. The cross section  $\sigma(pp \rightarrow b\bar{b}c\bar{c} + X)$  is evaluated by MadGraph to be  $(4.79 \pm 0.08) \times 10^3$  nb, which on using  $\Delta M = (2.0_{-0.4}^{+0.5})$  GeV yields the following fragmentation fraction and the corresponding cross section:

$$f(bc \rightarrow H_{\{bc\}}) = (5.7_{-1.4}^{+2.4})\%, \quad (16)$$

$$\sigma(pp \rightarrow H_{\{bc\}} + X) = (273_{-66}^{+113}) \text{ nb}. \quad (17)$$

Combined with Eq. (12) for the fragmentation fraction, we get

$$\sigma(pp \rightarrow T_{[\bar{u}\bar{d}]}^{\{bc\}} + X) = (48_{-12}^{+19}) \text{ nb}, \quad (18)$$

with  $p_T(T_{[\bar{u}\bar{d}]}^{\{bc\}}) < 20$  GeV. Assuming a detection efficiency of  $10^{-6}$ , we anticipate  $\mathcal{O}(10^3)$   $T_{[\bar{u}\bar{d}]}^{\{bc\}}$  candidate events in the currently available LHCb data set, and approximately a half of this number for the related tetraquarks  $T_{[\bar{u}\bar{s}]}^{\{bc\}}$  and  $T_{[\bar{d}\bar{s}]}^{\{bc\}}$ . 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  $T_{[\bar{u}\bar{d}]}^{\{bc\}}$  is estimated in Ref. [10] 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 an  $s$ -quark, are pitched at 7406 MeV, some 170 MeV above the  $B_s D$  threshold [10], considerably broadening the resonances.

Finally, the cross section  $\sigma(pp \rightarrow b\bar{b}c\bar{c} + X)$  at 13 TeV is evaluated by MadGraph to be  $(8.76 \pm 0.19) \times 10^3$  nb. Repeating the steps indicated for the 8 TeV case, we estimate the cross section at 13 TeV to increase by ap-

proximately a factor 1.9, yielding

$$\sigma(pp \rightarrow T_{[\bar{u}d]}^{[bc]}) = (88_{-22}^{+33}) \text{ nb.} \quad (19)$$

with  $p_T(T_{[\bar{u}d]}^{[bc]}) < 20 \text{ GeV}$ .

With the LHCb integrated luminosity of  $50 \text{ fb}^{-1}$ , to be reached in Runs 1-4, well over  $10^9 T_{[\bar{u}d]}^{[bc]}$  events will be produced.

We would like to thank Estia Eichten, Tim Gershon, Marek Karliner, Luciano Maiani, Alexander Parkhomenko, Antonello Polosa, Gerrit Schierholz, Sheldon Stone, Cen Zhang and Zhi-Jie Zhao for helpful discussions. This work is supported in part by the National Natural Science Foundation of China under Grant Nos. 11575110, 11655002, 11735010, the Natural Science Foundation of Shanghai under Grant No. 15DZ2272100, and the DFG Forschergruppe FOR 1873 ‘‘Quark Flavour Physics and Effective Field Theories’’.

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\* Electronic address: [ahmed.ali@desy.de](mailto:ahmed.ali@desy.de)

† Electronic address: [qin@physik.uni-siegen.de](mailto:qin@physik.uni-siegen.de)

‡ Electronic address: [wei.wang@sjtu.edu.cn](mailto:wei.wang@sjtu.edu.cn)

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