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Heaviest bound baryons production at the Large Hadron Collider

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We calculate the hadronic production of three heaviest bound baryons Ω_{bbb}, Ω^*_{bbc}, and Ω_{bbc} at hadron colliders at tree level. We present the integrated cross section and differential cross section distributions in this paper.

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I. INTRODUCTION

There are six flavors of quarks, u, d, s, c, b, and t, in the Standard Model. The lifetime of t quark is so short that t quark could not become a constituent quark in a bound state. As a result, the heaviest baryon in the ground state must be made up of three b quarks named Ω_{bbb}, and the next one must be made up of two b quarks and one c quark named Ω^*_{bbc} and Ω_{bbc}, according to the spins of the baryons. As an analogue of the heavy quarkonium, these baryons are an important probe of QCD and an ideal place for studying the interaction among three heavy quarks. As the Bc meson, these baryons can decay only by weak interactions. So, they also provide a clean environment for studying the weak interactions.

The triply heavy barons have been studied in theory for a long time. And the mass spectra of these three baryons have been calculated in different models [1–4]. In most of them, the masses of Ω_{bbb}, Ω^*_{bbc}, and Ω_{bbc} are about 14.2–14.8, 11.2–11.5, and 11.1–11.5 GeV, respectively. The masses of these baryons are so large that it is hard to produce them in normal colliders. There is not yet any information available from experiments on the triply heavy baryons. The Large Hadron Collider (LHC) provides a good chance to detect these triply heavy baryons because of its high colliding energy and high luminosity. In the past years, the production of these baryons has been calculated in kinds of colliders [5–7]. In Ref. [6], the production of these three triply heavy baryons at the LHC has been calculated by the fragmentation method. But there are two obvious mistakes. In that paper, the fragmentation function is given in the perturbative theory in Feynman gauge, although, as pointed out in Ref. [8], the fragmentation function can be correct only when it is calculated in axial gauge. Also, in Ref. [6], the authors do the calculation using two Feynman diagrams. Actually, there are seven basic Feynman diagrams that are shown in Fig. 1 in Sec. II of this paper, thus the results in that paper are suspect. Here, we calculate the direct hadronic production of these three heaviest baryons in the leading order at the LHC.

These baryons can be described by the nonrelativistic QCD (NRQCD) as a result of the large mass of the heavy quark, which is much larger than Λ_{QCD}. In the leading order, the direct production of the triply heavy baryon can be factorized into two parts, the short-distance coefficient corresponding to the production of three pairs of heavy quarks and the long-distance matrix corresponding to the coupling of three heavy quarks to the baryon. In the following, we will show how to calculate these two parts explicitly.

The rest of the paper is organized as follows: In Sec. II, we present the calculation of the production of the heaviest baryons; numerical results and conclusions are given in Sec. III.

II. CALCULATION OF PRODUCTION OF THE HEAVIEST BARYONS

A baryon must be in the color singlet. This means its color wave function must be $\frac{1}{\sqrt{6}}\varepsilon^{\xi_1\xi_2\xi_3}Q_{1\xi_1}Q_{2\xi_2}Q_{3\xi_3}$, which is antisymmetric.[1] For a ground baryon, its spin can only be $\frac{3}{2}$ or $\frac{1}{2}$. Because of the statistical antisymmetry of the fermion system, the symmetry of the orbital angular momentum wave function, and the antisymmetry of the color wave function, the spin wave function of the ground baryon made up of three b quarks must be symmetric. This means the spin of Ω_{bbb} must be $\frac{3}{2}$. For the same reason, the spin of the two b quarks' subsystem in the baryon made up of two b quarks and one c quark must be 1. As a result, the spin of the baryon made up of two b quarks and one c quark could be $\frac{3}{2}$ or $\frac{1}{2}$. And, we use Ω^*_{bbc} standing for the one with

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[1] ξ_i ($i = 1, 2, 3$) is the color index of the heavy quark Q_i.

spin $\frac{3}{2}$ and Ω_{bbc} standing for the one with spin $\frac{1}{2}$, respectively.

Because the mass of the heavy quark is much larger than Λ_{QCD}, the relative motion of the heavy quarks in the triply heavy baryon is nonrelativistic, and the typical velocity, v, of the heavy quark is much smaller than 1 at the rest frame of the baryon. With $v \ll 1$, the mass m, the typical momentum mv, and the typical off-shell energy mv^2 of the heavy quark are hierachical, namely $m \gg mv \gg mv^2$. Then NRQCD [9] can be used to describe the triply heavy baryon conveniently. In NRQCD, we can describe the normalized wave function of the triply heavy baryon in the ground state as

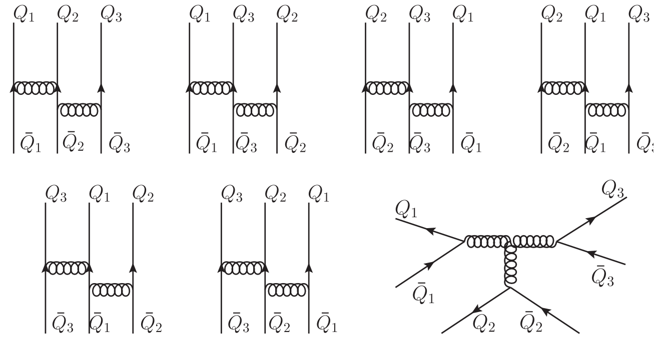

FIG. 1. Seven basic topology structures of three pairs of heavy quarks with different flavors.

$$|\Omega_{Q_1Q_2Q_3}, S, S_Z\rangle = \sqrt{2M}\int \frac{d^3\vec{q}_1}{(2\pi)^3}\frac{d^3\vec{q}_2}{(2\pi)^3}\sum_{\xi_1,\xi_2,\xi_3}\sum_{\eta_1,\eta_2,\eta_3}\frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}\langle S, S_Z|\eta_1, \eta_2, \eta_3\rangle \frac{1}{\sqrt{2E_1 2E_2 2E_3}}\frac{1}{\sqrt{d!}}\psi(\vec{q}_1, \vec{q}_2)$$
$$\times |Q_1, \xi_1, \eta_1, \vec{q}_1\rangle |Q_2, \xi_2, \eta_2, \vec{q}_2\rangle \times |Q_3, \xi_3, \eta_3, \vec{q}_3 = -\vec{q}_1 - \vec{q}_2\rangle, \tag{1}$$

where

$$\langle Q_i, \xi_i, \eta_i, \vec{q}_i|Q_j, \xi_j, \eta_j, \vec{q}_j\rangle = \delta_{Q_iQ_j}\delta_{\eta_i\eta_j}\delta_{\xi_i\xi_j}(2\pi)^3 2E_f\delta^{(3)}(\vec{q}_i - \vec{q}_j),$$

with η_i and $(E_i, \vec{q}_i)$ $(i = 1, 2, 3)$ as the spin and the four-momentum of the Q_i heavy quark; M is the mass of the baryon; $\langle S, S_Z|\eta_1, \eta_2, \eta_3\rangle$ is the Clebsch-Gordan (C-G) coefficient; S, S_Z are the spin of the baryon and its third component[2]; d equals 2 for Ω_{bbc} and Ω^*_{bbc} and 3 for Ω_{bbb}, and $\psi(\vec{q}_1, \vec{q}_2)$ is the wave function of the baryon in the momentum space which is normalized as follows

$$\int \frac{d^3\vec{q}_1}{(2\pi)^3}\frac{d^3\vec{q}_2}{(2\pi)^3}\psi^*(\vec{q}_1, \vec{q}_2)\psi(\vec{q}_1, \vec{q}_2) = 1.$$

The mass of the triply heavy baryon including two or there b quarks is too large to produce in normal high-energy particle colliders. With high luminosity and high energy, the LHC provides a good experimental environment to produce and detect these baryons. In the LHC, they can be produced directly by gg fusion and $q\bar{q}$ annihilation subprocesses. In the heavy quark limit, $v \ll 1$, the direct production process can be factorized into two parts—the hard production of three pairs of heavy quarks and the coupling of the three heavy quarks to the heavy baryon.

In the leading order (expansion in v), the dependence of the short distance on the q_1 and q_2 can be neglected and the momentum of the produced three heavy quarks have the relation of $p_1{:}p_2{:}p_3 = m_1{:}m_2{:}m_3$. Because of the independence of the short-distance coefficient on the q_i, the long-distance matrix will be proportional to the wave function of the baryon at the origin,

$$\Psi(0, 0) = \int \frac{d^3\vec{q}_1}{(2\pi)^3}\frac{d^3\vec{q}_2}{(2\pi)^3}\psi(\vec{q}_1, \vec{q}_2),$$

which we have evaluated using the model given in Ref. [3] and taken $\Psi^2(0, 0)$ to be 0.189 for Ω_{bbb} and 0.0146 GeV^6 for Ω_{bbc} and Ω^*_{bbc}.

A. Calculation of $gg \to (Q_1Q_2Q_3)_1^{S,S_Z}\bar{Q}_1\bar{Q}_2\bar{Q}_3$

Now, let us consider the short-distance coefficient. There are two subprocesses for the production of three pairs of heavy quarks—gluon-gluon fusion and quark-antiquark annihilation. Our numerical results show that the contribution of quark-antiquark annihilation subprocesses is much less than the contribution of the gluon-gluon fusion subprocess. Here we just show the calculation of the gluon-gluon fusion subprocess.

Coupling to a baryon, there are some constraints on the three heavy quarks. First of all, the three heavy quarks must couple to the color singlet and have the antisymmetric color configuration $\frac{1}{\sqrt{6}}\varepsilon^{\xi_1\xi_2\xi_3}Q_{1\xi_1}Q_{2\xi_2}Q_{3\xi_3}$. The spin wave function must be the same as the one of the baryon to which the three heavy quarks couple. Besides, the velocities of the heavy quarks are approximately the same. We use $(Q_1Q_2Q_3)_1^{S,S_Z}$, standing for the three heavy quarks satisfying these three conditions.

As pointed out in Ref. [7], when the three heavy quarks have different flavors, there are 727 Feynman diagrams for $gg \to (Q_1Q_2Q_3)_1^{S,S_Z}\bar{Q}_1\bar{Q}_2\bar{Q}_3$, which can be given by inserting two initial gluons into the seven basic topology

[2] S equals to $\frac{1}{2}$ for the production of Ω_{bbc}, and $\frac{3}{2}$ for the production of Ω^*_{bbc} and Ω_{bbb}. S_Z equals $-S, -S+1, \ldots, S$.

structures given in Fig. 1 in all allowed positions.[3] For the subprocess of $gg \to (bbc)_1^{S,S_z}\bar{b}\,\bar{b}\,\bar{c}$, the produced particles have two fermion permutations, $(b_1\bar{b}_1b_2\bar{b}_2c\bar{c})$ and $(b_1\bar{b}_2b_2\bar{b}_1c\bar{c})$.[4] And for the subprocess of $gg \to (bbb)_1^{\frac{3}{2},S_z}\bar{b}\,\bar{b}\,\bar{b}$, there are six fermion permutations for the produced three pairs of b quarks, which are $(b_1\bar{b}_1b_2\bar{b}_2b_3\bar{b}_3)$, $(b_1\bar{b}_2b_2\bar{b}_3b_3\bar{b}_1)$, $(b_1\bar{b}_3b_2\bar{b}_1b_3\bar{b}_2)$, $(b_1\bar{b}_2b_2\bar{b}_1b_3\bar{b}_3)$, $(b_1\bar{b}_3b_2\bar{b}_2b_3\bar{b}_1)$, and $(b_1\bar{b}_1b_2\bar{b}_3b_3\bar{b}_2)$. For each of these two/six fermion permutations, there are seven topology structures, and 727 Feynman diagrams. For $gg \to (bbc)_1^{S,S_z}\bar{b}\,\bar{b}\,\bar{c}$ subprocess, there are $727 \times 2 = 1454$ Feynman diagrams, and each of the 727 Feynman diagrams, given by inserting the initial gluons into the seven topology structures of the produced heavy quarks corresponding to the second fermion permutation, have an additional minus sign. For the subprocess of $gg \to (bbb)_1^{\frac{3}{2},S_z}\bar{b}\,\bar{b}\,\bar{b}$, there are $727 \times 6 = 4362$ Feynman diagrams, and each of the $727 \times 3 = 2181$ Feynman diagrams, given by inserting the two initial gluons into the 21 topology structures of the three heavy quarks of the last three fermion permutations, has an additional minus sign.

It is a hard work to calculate so many Feynman diagrams. In the calculation, we take advantage of the features of the three produced heavy quarks to simplify the calculation. We can see that the momenta of the identical produced heavy quarks can be considered as equal in the calculation. And the spin wave function of the identical heavy quark system is symmetric with the color wave function of the system being antisymmetric. As a result, when we exchange two identical heavy quarks in the Feynman diagrams, the amplitudes without the color parts do not change, and each of the corresponding color factors gets an additional minus sign. Then we get that the Feynman diagrams given by inserting initial gluons into the heavy quark topology structure of different fermion permutations give the same contributions. This means that we just need to calculate the 727 Feynman diagrams corresponding to the first permutation of the two/six permutations of the produced heavy quarks.

In the calculation of the amplitudes of the basic 727 Feynman diagrams, we calculate the color factors and matrixes without color parts separately. For a Feynman diagram with a four-gluon vertex, there are three different color factors and three corresponding matrixes. Then, for the basic 727 Feynman diagrams, we have to calculate $727 + 2 \times 34 = 795$ color factors and matrixes. As mentioned above, the color configuration of the produced heavy quarks is $\frac{1}{\sqrt{6}}\varepsilon^{\xi_1\xi_2\xi_3}Q_{1\xi_1}Q_{2\xi_2}Q_{3\xi_3}$. Using the color-flow method in Ref. [10], we get twelve different color structures C_i ($i = 1, 2, \ldots, 12$) for the subprocess of $gg \to (Q_1Q_2Q_3)_1^{S,S_z}\bar{Q}_1\bar{Q}_2\bar{Q}_3$, which are listed in the following:

$$\begin{aligned}
&C_1 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a\lambda^b)_{\xi_1\chi_2}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_3}, \quad C_2 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^b\lambda^a)_{\xi_1\chi_2}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_3}, \quad C_3 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a\lambda^b)_{\xi_1\chi_1}\delta_{\xi_2\chi_2}\delta_{\xi_3\chi_3},\\
&C_4 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^b\lambda^a)_{\xi_1\chi_1}\delta_{\xi_2\chi_2}\delta_{\xi_3\chi_3}, \quad C_5 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a\lambda^b)_{\xi_1\chi_3}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_2}, \quad C_6 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^b\lambda^a)_{\xi_1\chi_3}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_2},\\
&C_7 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_1}(\lambda^b)_{\xi_2\chi_2}\delta_{\xi_3\chi_3}, \quad C_8 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_2}(\lambda^b)_{\xi_2\chi_1}\delta_{\xi_3\chi_3}, \quad C_9 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_2}(\lambda^b)_{\xi_2\chi_3}\delta_{\xi_3\chi_1},\\
&C_{10} = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_3}(\lambda^b)_{\xi_2\chi_2}\delta_{\xi_3\chi_1}, \quad C_{11} = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_3}(\lambda^b)_{\xi_2\chi_1}\delta_{\xi_3\chi_2}, \quad C_{12} = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_1}(\lambda^b)_{\xi_2\chi_3}\delta_{\xi_3\chi_2},
\end{aligned} \tag{2}$$

where $\chi_i = 1, 2, 3$ ($i = 1, 2, 3$) and a, $b = 1, 2, \ldots, 8$ are the color indices of the produced heavy antiquarks and two initial gluons, respectively. All the 795 color factors can be expressed with these twelve color structures. The total amplitude for the subprocess $gg \to (Q_1Q_2Q_3)_1^{S,S_z}\bar{Q}_1\bar{Q}_2\bar{Q}_3$ is

$$\mathcal{M}(gg \to (Q_1Q_2Q_3)_1^{(S,S_z)}\bar{Q}_1\bar{Q}_2\bar{Q}_3) = d!\sum_{k=1}^{795} CF_k\mathcal{M}_k = d!\sum_{k=1}^{12} C_k\Gamma_k, \tag{3}$$

where CF_k ($k = 1, 2, \ldots, 795$) are the color factors of the Feynman diagrams and $\mathcal{M}_k$ are the corresponding matrixes; Γ_k ($k = 1, 2, \ldots, 12$) are the combinations of the amplitudes of the basic Feynman diagrams related to the 12 color structures C_k.

We see that the former six topology structures in Fig. 1 are similar. As a result, we just need to calculate the color factors of the Feynman diagrams given by inserting initial

[3] Considering Feynman diagrams without the four-gluon vertex, there are 9 ways to insert the first gluon and 11 ways to insert the second gluon for each topology structure. Considering the Feynman diagrams with one four-gluon vertex, there are 2 ways to insert the two initial gluons for each of the first six topology structures shown in Fig. 1 and 22 ways to insert the initial gluons into the seventh topology structure. So, there are in total $9 \times 11 \times 7 + 2 \times 6 + 22 = 727$ Feynman diagrams.

[4] $(Q_1\bar{Q}_iQ_2\bar{Q}_jQ_3\bar{Q}_k)$ ($i, j, k = 1, 2, 3$ and $i \neq j \neq k$) means Q_1 in the same fermion line with $\bar{Q}_i$, Q_2 in the same fermion line with $\bar{Q}_j$ and Q_3 in the same fermion line with $\bar{Q}_k$.

TABLE I. Production cross sections (in unit pb) of the triply heavy baryons at the LHC with various p_T cuts ($p_T > p_{T\mathrm{cut}}$) and different collision energy $\sqrt{S}$. We take pseudorapidity cuts $|\eta| < 2.5$ for CMS and ATLAS and $1.9 < \eta < 4.9$ for the LHCb. The number in parenthesis shows the Monte Carlo uncertainty in the last digit.

⋯	$\sqrt{S}$	7 TeV		14 TeV	
⋯	⋯	CMS and ATLAS	LHCb	CMS and ATLAS	LHCb
⋯	η_{cut} / p_{Tcut}	$\|\eta\| < 2.5$	$1.9 < \eta < 4.9$	$\|\eta\| < 2.5$	$1.9 < \eta < 4.9$
Ω_{bbc}	0 GeV	0.0444(4)	0.0183(2)	0.0961(5)	0.0467(4)
⋯	5 GeV	0.0309(3)	0.00913(6)	0.0687(5)	0.0256(3)
⋯	10 GeV	0.0101(2)	0.00211(2)	0.0240(4)	0.00656(8)
Ω^*_{bbc}	0 GeV	0.117(1)	0.0519(6)	0.249(3)	0.129(2)
⋯	5 GeV	0.0767(5)	0.0233(3)	0.167(2)	0.0648(6)
⋯	10 GeV	0.0218(2)	0.00468(8)	0.0511(6)	0.0145(2)
Ω_{bbb}	0 GeV	0.0201(1)	0.00850(3)	0.0468(2)	0.0234(1)
⋯	5 GeV	0.0155(1)	0.00490(2)	0.0369(2)	0.0145(1)
⋯	10 GeV	0.00618(3)	0.00137(1)	0.0155(1)	0.00451(3)

gluons into the first topology structure and reexpress them with the 12 color structures listed in Eq. (2) as a base. Then we can calculate and express the color factors of Feynman diagrams given by inserting the initial gluons into the second, third, fourth, fifth, and sixth topology structures by a simple transformation code using the color factors of the Feynman corresponding to the first topology structure, which we have calculated and expressed. Also, by a simple substraction code, we can calculate and express the color factors of the Feynman diagrams given by inserting the initial gluons into the seventh topology structure. To calculate the amplitudes without color parts, we make a program in FORTRAN. The code is made up of one main routine and many subroutines. The subroutines are used to calculate the spinors and polarization vectors of the external legs and the types of vertices and propagators. Calling the subroutines in different orders in the main routine, the 795 amplitudes without color parts are calculated. To ensure the correctness of the code, we have tested the gauge invariance for each of the invariant amplitudes Γ_k ($k = 1, 2, \ldots, 12$) corresponding to the 12 color structures.

III. NUMERICAL RESULTS AND CONCLUSIONS

Intersecting with the parton model, the cross sections of the $pp \to Q_1\bar{Q}_1Q_2\bar{Q}_2Q_3\bar{Q}_3X$ progress are

$$\sigma = \frac{1}{d!}\int dx_1 dx_2 f_{g_1}(x_1, \mu_F) f_{g_2}(x_2, \mu_F) \int d\hat{\sigma}(gg \to \Omega_{Q_1Q_2Q_3}\bar{Q}_1\bar{Q}_2\bar{Q}_3, \mu_F), \quad \text{with}$$

$$d\hat{\sigma} = \sum_{S_Z, s_i} \frac{(2\pi)^4}{2\hat{s}} \delta^4(k_1 + k_2 - P - v_1 - v_2 - v_3) d\Pi_4 \frac{1}{N} \sum_{a,b,\chi_i} |\mathcal{A}(gg \to \Omega_{Q_1Q_2Q_3}\bar{Q}_1\bar{Q}_2\bar{Q}_3)|^2,$$

$$\text{where } d\Pi_4 = \frac{d^3P}{(2\pi)^3 2E} \frac{d^3v_1}{(2\pi)^3 2E_{v_1}} \frac{d^3v_2}{(2\pi)^3 2E_{v_2}} \frac{d^3v_3}{(2\pi)^3 2E_{v_3}} \quad \text{and}$$

$$A(gg \to \Omega_{Q_1Q_2Q_3}\bar{Q}_1\bar{Q}_2\bar{Q}_3) = \frac{\sqrt{2M}}{\sqrt{2m_1 \cdot 2m_2 \cdot 2m_3}} \frac{\Psi(0,0)}{\sqrt{d!}} \mathcal{M}(gg \to (Q_1Q_2Q_3)_1^{(S,S_Z)}\bar{Q}_1\bar{Q}_2\bar{Q}_3), \tag{4}$$

where s_i and v_i ($i = 1, 2, 3$) are the spin and four-momentum of the antiquarks $\bar{Q}_i$; $f_g(x, \mu_F)$ is the parton distribution function of the gluon in the proton, for which we take Cteq6l [11]; μ_F is the factorization energy scale; and N equals 64 for the color average of the initial gluons. There are uncertainties arising from the choice of μ_F and the running coupling constant α_s for strong interaction. We do the calculation using α_s at the one-loop order given in Ref. [12] and with the choice of $\mu_F = \mu_R/2$, where μ_R is the transverse mass of the produced baryon, namely $\mu_R^2 = p_T^2 + M^2$.[5] Taking $m_c = 1.5$ and $m_b = 4.9$ GeV, we listed the numerical cross sections with the types of p_T cuts on the produced heavy baryons in Table I. The differential cross section distributions versus the transverse momentum and rapidity of the produced baryon are given

[5]In this paper, p_T means the transverse momentum of the produced triply heavy baryon.

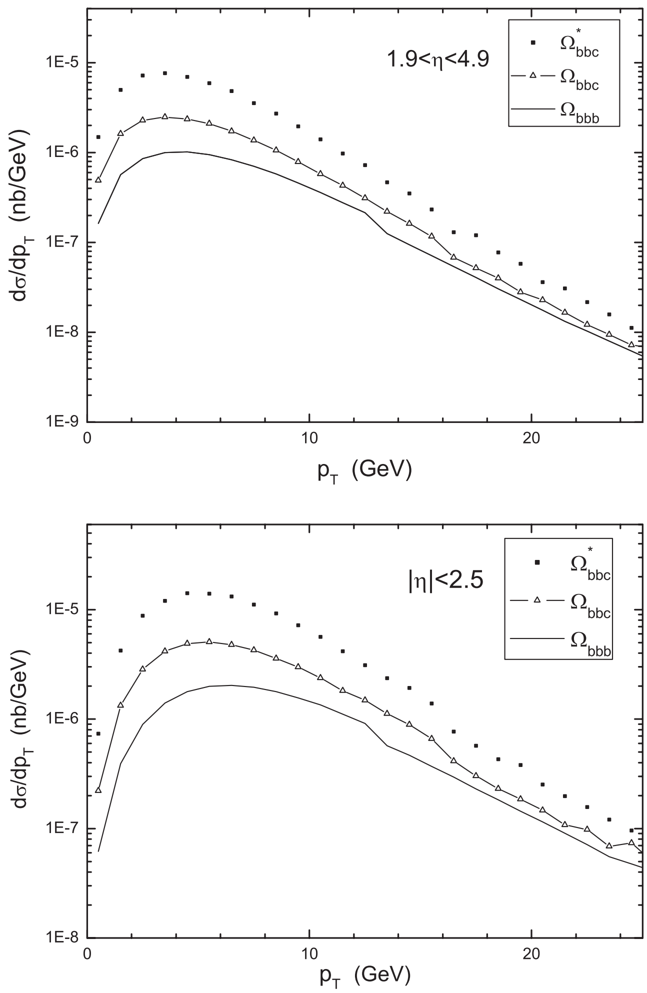

FIG. 2. Distributions of the differential production cross sections versus the transverse momentum of the triply heavy baryons produced at the LHCb and CMS (ATLAS) with $\sqrt{S} = 7$ TeV.

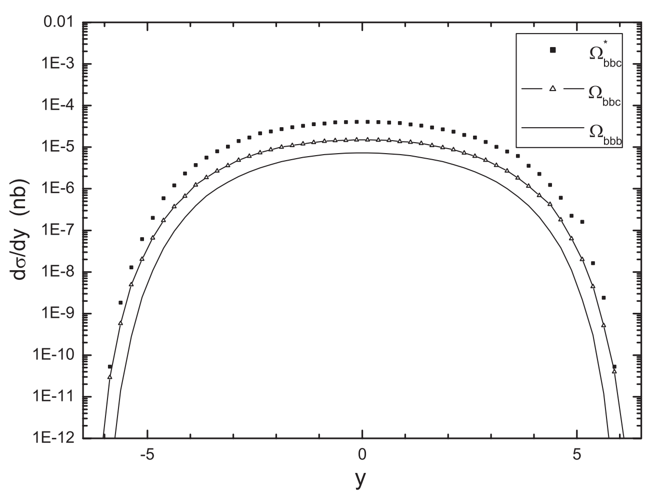

FIG. 3. Distributions versus the rapidity of the triply heavy baryons produced in $pp \to \Omega_{bbb}\bar{b}\,\bar{b}\,\bar{b}X$, $\Omega_{bbc}\bar{b}\,\bar{b}\,\bar{c}X$, and $\Omega^*_{bbc}\bar{b}\,\bar{b}\,\bar{c}X$ channels at the LHC with $\sqrt{S} = 7$ TeV.

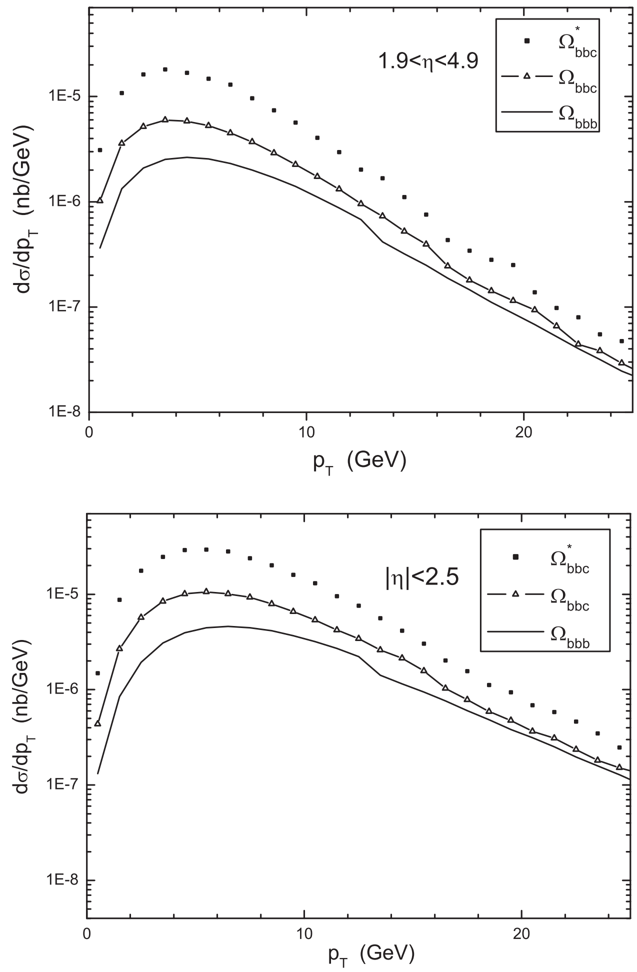

FIG. 4. Distributions of the differential production cross sections versus the transverse momentum of the triply heavy baryons produced at the LHCb and CMS (ATLAS) with $\sqrt{S} = 14$ TeV.

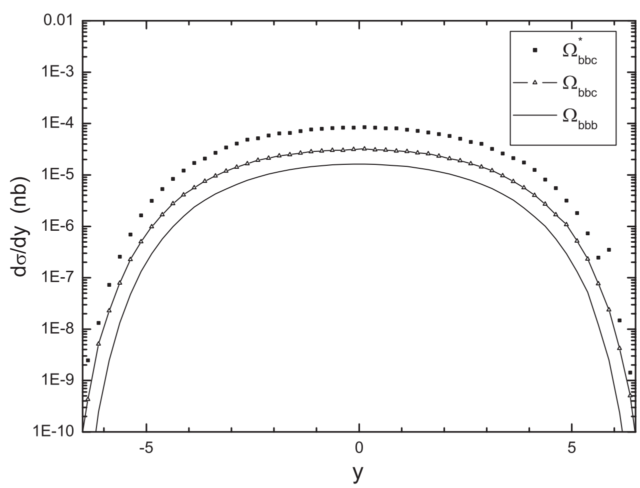

FIG. 5. Distributions versus the rapidity of the triply heavy baryons produced in $pp \to \Omega_{bbb}\bar{b}\,\bar{b}\,\bar{b}X$, $\Omega_{bbc}\bar{b}\,\bar{b}\,\bar{c}X$, and $\Omega^*_{bbc}\bar{b}\,\bar{b}\,\bar{c}X$ channels at the LHC with $\sqrt{S} = 14$ TeV.

in Figs. 2–5. Some parts in the P_T distributions are not smooth due to a Vegas simulation error.

We see that both the integrated cross sections and differential cross sections are proportional to $\Psi^2(0,0)$ and $\alpha_s^6(\mu_F)$. Then the numerical results can be changed by one or even two orders, using different wave functions at the origin of the triply heavy baryons, different running coupling constants, and different energy scale choices.

To reconstruct these heaviest baryons, their particular signatures need to be studied. We see that these baryons can decay only through weak interactions. Now let us give a brief analysis on the two kinds of cascade decay models—nonleptonic decay and semileptonic decay. For Ω_{bbc} (Ω^*_{bbc}), an interesting cascade nonleptonic decay is $\Omega_{bbc}(\Omega^*_{bbc}) \to \Omega^{(*)}_{ccb} + \pi^-(\rho^-)$ with $\Omega^{(*)}_{ccb}$ decaying in the nonleptonic model to $\Omega_{sss} + 3\pi^+(\rho^+) + \pi^-(\rho^-)$ [7]. The corresponding semileptonic decay model for Ω_{bbc} (Ω^*_{bbc}) is $\Omega_{bbc}(\Omega^*_{bbc}) \to \Omega^{(*)}_{ccb} + l^- + \bar{\nu}_l$ with $\Omega^{(*)}_{ccb}$ decaying in a cascade nonleptonic model, which has been studied in a Y-shaped confinement potential in Ref. [13].

For Ω_{bbb}, one interesting cascade nonleptonic decay is $\Omega_{bbb} \to \Omega^{(*)}_{bbc} + \pi^-(\rho^-)$ with $\Omega^{(*)}_{bbc}$ decaying by the nonleptonic model given above. The corresponding semileptonic decay model is $\Omega_{bbb} \to \Omega^{(*)}_{bbc} + l^- + \bar{\nu}_l$ with $\Omega^{(*)}_{bbc}$ decaying by a cascade semileptonic model, which has also been studied in Ref. [13].

These heaviest baryons are very interesting hadrons to explore, for they provide particular information about strong interactions, hadron structure, and weak decay. Our results show that it is possible to detect them at the LHC when both the integrated luminosity and collision energy are proved.

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[12]
$$\alpha_s(\mu) = \frac{\alpha_s(m_Z)}{1 + \frac{b_0}{2\pi}\alpha_s(m_Z)\log(\mu/m_Z)}, \quad \text{with}$$
$$b_0 = 11 - \frac{2}{3}nf, \tag{5}$$
where μ is the energy scale, $m_Z = 91.18$ GeV and $\alpha_s(m_Z) = 0.118$. And nf is taken to be 4 when $\mu \le 2m_b$ and 5 when μ is larger than $2m_b$.

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