$B_c$ Production in Higgs Boson Decays

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Abstract

$B_c$ production rate in Higgs boson decays is evaluated in NRQCD framework. Given Higgs total decay width is about 4.20 MeV and the vector $B_c^*$ meson decays completely to the ground state, we find that the branching fraction of $B_c$ meson production in Higgs decays is $8.50 \times 10^{-4}$, where both leading QCD and QED contributions are included. This process is hence detectable in the high-luminosity/energy LHC. It is found that the coupling of $Hb\bar{b}$ dominate the processes, contributions from the triangle top quark loop and other couplings ($Hc\bar{c}$, $HWW$ and $HZZ$) are small. In confronting to the quarkonia production, we find that the fraction rate of $B_c$ production is more than an order of magnitude bigger than those of charmonium and bottomonium production in Higgs decays. Moreover, various uncertainties and differential distributions of the concerned processes are analysed carefully.

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I. INTRODUCTION

In July 2012, the Higgs boson of the Standard Model has been found by ATLAS [1] and CMS [2] at Large Hardron Collider (LHC), which is a milestone in particle physics. Recent results and review papers on Higgs measurements and searches at ATLAS and CMS can be found in Ref.s [3–7]. Due to the insufficient Higgs samples and the detectors’ limits, experimental study on the couplings of Higgs and fermions/bosons leaves much to be desired.

To open the era of precise Higgs physics, upgraded LHC, even new colliders are needed. High luminosity/energy scenarios are designed for LHC (HL/HE-LHC) [8]. Running at center-of-mass energy $\sqrt{s} = 14 \text{ TeV}$, cross-section of Higgs boson production at LHC is about 55 $\text{pb}$ (gluon-gluon fusion process dominates) [9]. Given that the integrated luminosity is 3 $\text{ab}^{-1}$, HL-LHC would produce $1.65 \times 10^8$ Higgs events. While at HE-LHC who runs at $\sqrt{s} = 33 \text{ TeV}$, the cross-section of Higgs production would be about 200 $\text{pb}$, hence Higgs events can be 3.5 times bigger. For the proposed Higgs factory, Circular Electron-Positron Collider (CEPC) running at $\sqrt{s} = 250 \text{ GeV}$ with an integrated luminosity of 5 $\text{ab}^{-1}$, the cross-section of $e^+e^- \rightarrow H^0Z^0$ is about 0.219 $\text{pb}$, resulting in $1.10 \times 10^6$ Higgs events only [10]. However at CEPC, since Higgs candidates can be identified through the recoil mass method without tagging its decays, Higgs production and decay are separated apart directly. Moreover at a $e^+e^-$ collider, physicists can perform measurements of model-independent Higgs total width and exclusive Higgs decay channels much better. The absolute values of Higgs coupling to bosons, gluons and heavy fermions can also be measured. When updated to the Super Proton-Proton Collider (SPPC), researchers can even measure the Higgs self-coupling, which is regarded as the holy grail of experimental particle physics.

With the excellent platforms, rare Higgs boson decay processes, like the heavy quarkonia production in Higgs decays, might be observed for the first time. Pioneer investigation on the search of $H^0 \rightarrow J/\psi\gamma$ and $H^0 \rightarrow \Upsilon(nS)\gamma$ has been carried out by ATLAS [11]. Theoretically, some related calculations have been done [12–15]. Within the Non-Relativistic QCD (NRQCD) formulism [16, 17] and light-cone methods [18, 19], both direct and indirect production mechanism and relativistic corrections to $H^0 \rightarrow J/\psi\gamma$ and $H^0 \rightarrow \Upsilon(nS)\gamma$ are studied [13]. In addition, a detailed and complete analysis of $H^0 \rightarrow (\rho, \phi, \omega, J/\psi, \Upsilon(nS)) + \gamma$ at the one-loop level is performed carefully [14]. Further, the complete inclusive production of heavy quarkonia ($J/\psi$ and $\Upsilon$) in Higgs boson decays are investigated in both color-
singlet and color-octet mechanism \[15\]. Moreover, processes of Higgs boson decays to a quarkonium associated with a \( Z^0 \) boson are also analyzed \[20\], as well as double production of the quarkonia in Higgs decays \[21\]. Of course, all these rare decay channels might be observed and studied at the future HL/HE-LHC or CEPC/SPPC.

Containing two different flavors of heavy quarks, the \( B_c \) mesons are very good research objects to reveal the nature of strong and weak interactions. Besides the study of direct one, indirect \( B_c \) production through heavy particles decay are attractive. It can inform us not only the nature \( B_c \) itself, but also the properties of the parent particles. Study of \( B_c \) production through \( W \) boson decays \[22, 23\], top quark decays \[24–26\] and \( Z^0 \) boson decays \[27–30\] have been studied systematically and carefully. Particularly, Ref. \[26\] and Ref.s \[29, 30\] show us the precise next-to-leading order calculation of \( B_c^{(*)} \) production, which leads the calculation of \( B_c^{(*)} \) production to the precise study level.

In this work, we will study the \( B_c \) production in Higgs boson decays within NRQCD formulism, an estimation of events at HL/HE-LHC and a comparison with Higgs decays to the heavy quarkonia are also included.

The rest of this paper is organized as follows: Section II presents our formalism and calculation method, numerical evaluation and some discussion of the results are shown in Section III, and Section IV gives a summary and some conclusions.

## II. CALCULATION SCHEME DESCRIPTION AND FORMALISM

Feynman diagrams for processes \( H^0(k) \rightarrow B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_6) \) are displayed in Fig.1. In our calculation, both QCD and QED contributions have been considered. According to the NRQCD framework, the decay width can be factorized as

\[
\Gamma = \sum_n \Gamma_n(H^0 \rightarrow (c\bar{b})[n] + \bar{c} + b) \times \langle O[n] \rangle.
\]  

(1)

In which the width \( \Gamma_n \) represents the short-distance coefficients at the partonic level which can be calculated perturbatively, long-distance matrix element \( \langle O[n] \rangle \) contains all the non-perturbative hardronization information, and \( n \) stands for the involved \( c\bar{b} \) Fock states. In our computation, two color-singlet states \((c\bar{b})[1S_0] \) and \((c\bar{b})[3S_1] \) (donated as \( B_c \) and \( B_c^* \) respectively) are taken into consideration. And their matrix elements can be related directly.
FIG. 1: The QCD/QED Feynman diagrams of processes $H^0(k) \to B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_6)$, where convolved/waved lines represent the gluon/photon propagators.

to the regularized Shrödinger wave functions at the origin:

$$\langle B_c | \mathcal{O}[^1S_0] | B_c \rangle \approx \frac{1}{4\pi} |\bar{R}_{B_c}|^2,$$

$$\langle B_c^{*} | \mathcal{O}[^3S_1] | B_c^{*} \rangle \approx \frac{1}{4\pi} |\bar{R}_{B_c^{*}}|^2,$$

where radial wave functions $\bar{R}_{B_c^{(*)}}$ can be computed by potential models [31]. Note that the spin-splitting effect of the wave functions is ignored in our calculation, i.e. $|\bar{R}_{B_c}| = |\bar{R}_{B_c^{*}}|$. 

For the partonic coefficient $\hat{\Gamma}_n$, its differential form can be expressed as

$$d\hat{\Gamma}_n = \frac{1}{2m_H} \sum |M(n)|^2 d\Phi_3,$$

where $\sum$ sums over the spin, color and polarization, $\Phi_3$ is the 3-body phase space of the final states, $m_H$ is the mass of Higgs boson. The amplitude $M(n)$ which contains both QCD and QED contributions has the form of

$$M(n) = \sum_{i=1}^{4} (C_{QCD} + C_{QED}) \bar{u}(p_6) \cdot M'_i(n) \cdot v(p_5),$$

where $C_{QCD} = \frac{eC_Fg^2}{2m_W\sin\theta_W}$ and $C_{QED} = -\frac{e^3}{9m_W\sin\theta_W}$, with $m_W$ is the mass of W boson, $\sin\theta_W$ is the sine of Weinberg angle $\theta_W$. And $M'_i(n)$ can be read from Fig. 1 directly with the help
of Mathematica package FeynArt\[32\], their analytical expressions are

\[ M_1'(n) = \frac{m_c \gamma_\nu \cdot \Pi(n) \cdot (-p_4 - p_5 - p_6 + m_c) \cdot \gamma^\nu}{(p_4 + p_6)^2((p_4 + p_5 + p_6)^2 - m_c^2)}, \]

\[ M_2'(n) = \frac{m_b \gamma_\nu \cdot (\bar{p}_3 + \bar{p}_5 + \bar{p}_6 + m_b) \cdot \Pi(n) \cdot \gamma^\nu}{(p_3 + p_5)^2((p_3 + p_5 + p_6)^2 - m_b^2)}, \]

\[ M_3'(n) = \frac{m_c \gamma_\nu \cdot \Pi(n) \cdot \gamma^\nu \cdot (\bar{p}_3 + \bar{p}_4 + \bar{p}_6 + m_c)}{(p_4 + p_6)^2((p_4 + p_5 + p_6)^2 - m_c^2)}, \]

\[ M_4'(n) = \frac{m_b (-\bar{p}_3 - \bar{p}_4 - \bar{p}_5 + m_b) \cdot \gamma_\nu \cdot \Pi(n) \cdot \gamma^\nu}{(p_3 + p_5)^2((p_3 + p_4 + p_5)^2 - m_b^2)}. \]  

In which, \( \Pi(n) \) is the projector of Fock state \( n \), which has the form of \[33\]

\[ \Pi(n) = \frac{1}{2\sqrt{m_c + m_b}} \epsilon(n)(p_0 + m_c + m_b) \frac{\delta_{ij}}{\sqrt{N_c}}, \]  

where \( \epsilon^{(1)S_0} = \gamma_5 \), \( \epsilon^{(3)S_1} = \gamma^\alpha \) with \( \epsilon^\alpha \) is the polarization vector of \( ^3S_1 \) state, \( i \) and \( j \) are the color indexes of the constitute quarks.

Submitting Eqs. \[34\] into Eq. \[3\], squared amplitude \( |M(n)|^2 \) can be obtained with the help of the Mathematica package FeynCalc \[34\]. To construct the differential phase space \( d\Phi_3 \), we adopt partly the fortran codes of the package FormCalc \[35\]. And with its help, the kinematic and dynamic variables can be extracted out easily to carry out the numerical analysis of differential distributions.

### III. NUMERICAL RESULTS AND ANALYSIS

In the numerical computation, the one-loop running coupling constant is employed. And the values of radial wave functions can be found in Ref. \[31\]. In our calculation, wave functions evaluated by QCD (Buchmüller-Tye) potential model is adopted. For convenience, some input parameters are listed as follows \[36\]:

\( m_c = 1.5 GeV, m_b = 4.9 GeV, m_H = 125.7 GeV, \)

\( \alpha = 1/127, \alpha_s(2m_c) = 0.326, \alpha_s(2m_b) = 0.214, \)

\( m_W = 80.4 GeV, sin\theta_W = \sqrt{0.231}, m_{B^{(*)}} = m_b + m_c, \)

\( m_Z = 91.2 GeV, V_{cb} = 0.0414, m_t = 173.2 GeV. \)  

In Table \[4\] the QCD and QED contributions to decay widths \( \Gamma(H^0 \rightarrow B_c^{(*)} + \bar{c} + b) \) are presented. In comparison with the QCD one, QED contribution is negligible. According to
TABLE I: QCD and QED contributions to the decay widths $\Gamma(H^0 \to B^*_c + \bar{c} + b)$ (units: KeV).

|            | $B_c$     | $B^*_c$    |
|------------|-----------|------------|
| QCD        | 1.53      | 2.08       |
| QED        | $5.71 \times 10^{-5}$ | $7.75 \times 10^{-5}$ |
| cross-terms| -0.0187   | -0.0254    |
| total decay width | 1.51      | 2.06       |

TABLE II: Uncertainties of the decay widths $\Gamma(H^0 \to B^*_c + \bar{c} + b)$ (units: KeV) caused by the matrix element $\langle B^*_c | O[1S_0(3S_1)] | B^*_c \rangle$ (units: GeV$^3$). Percentages in brackets are corrections relative to the QCD (B-T) one.

| $\langle B^*_c | O[1S_0(3S_1)] | B^*_c \rangle$ | $B_c$     | $B^*_c$    |
|------------------|-----------|------------|
| QCD (B-T): 0.1306 | 1.51      | 2.06       |
| Power-law: 0.1361 | 1.57(+4%) | 2.15(+4%)  |
| Logarithmic: 0.1200 | 1.39(-8%) | 1.89(-8%)  |
| Cornell: 0.2534  | 2.93      | 4.00       |

For our complete leading-order NRQCD calculation, the uncertainty sources mainly include the non-perturbative matrix element $\langle O[n] \rangle$, the mass parameters $m_b$ and $m_c$, and the running coupling constant $\alpha_s(\mu)$. To estimate the uncertainties from matrix element $\langle B^*_c | O[1S_0(3S_1)] | B^*_c \rangle$, we adopt the four potential models in Ref. [31], and the corresponding decay widths are displayed in Table II. If adopting the Power-law potential and Logarithmic potential as the upper and lower limits respectively, we obtain the corrections to the widths are about +4% and −8% accordingly for both $B_c$ and $B^*_c$ cases. In Table III decay widths with varying quark masses are presented, in which when $m_b(m_c)$ varies, the
TABLE III: Uncertainties of the decay widths $\Gamma(H^0 \rightarrow B_c^{(*)} + \bar{c} + b)$ (units: KeV) caused by the mass parameters $m_b$ and $m_c$ (units: GeV). When $m_b(m_c)$ varies, the $m_c(m_b)$ is fixed at its central value.

| $m_{b,c}$ | $B_c$ | $B_c^*$ |
|-----------|-------|--------|
| $m_b = 4.9^{+0.2}_{-0.2}$ | $1.51^{+0.12}_{-0.12}$ | $2.06^{+0.20}_{-0.19}$ |
| $m_c = 1.5^{+0.1}_{-0.1}$ | $1.51^{+0.27}_{-0.35}$ | $2.06^{+0.40}_{-0.53}$ |

$m_c(m_b)$ is fixed at its central value. The uncertainty caused by varying $m_b$ is about 8% and 10% for $B_c$ and $B_c^*$ respectively, while that caused by varying $m_c$ is more than two times bigger. By taking QED Feynman diagrams into account, the decay widths now are no longer proportional to $\alpha_s^2(\mu)$ alone, but have the form of

$$\Gamma_{B_c}(\alpha_s) = 33.4\alpha_s^2 - 0.0873\alpha_s + 0.000057,$$

$$\Gamma_{B_c^*}(\alpha_s) = 45.3\alpha_s^2 - 0.119\alpha_s + 0.000077. \quad (8)$$

Considering that the coupling constant $\alpha_s(\mu)$ decreases by 10% from $\alpha_s(2m_b)$, then decay width $\Gamma_{B_c}$ would decrease from 1.51 KeV down to 1.22 KeV, and $\Gamma_{B_c^*}$ goes from 2.06 KeV down to 1.66 KeV. Both have about 20% depression.

FIG. 2: The triangle loop (top quark only) and W/Z boson propagated Feynman diagrams of processes $H^0(k) \rightarrow B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_6)$. 

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TABLE IV: Corrections to the decay widths $\Gamma(H^0 \rightarrow B_c^{(*)} + \bar{c} + b)$ (units: KeV) raised from Fig. 2. Some input parameters are listed in Eq. (7), $\alpha_{ew}$ is the electroweak coupling constant and $V_{cb}$ is the CKM matrix element for the mixing of $c, b$ quarks. Percentages in the brackets are the ratios of various corrections relative to the Fig. 1 (QCD only) one. Note that only QCD Feynman diagrams in Fig. 1 are considered.

| Contributions | Order | $B_c$ | $B_c^*$ |
|---------------|-------|-------|--------|
| Fig. 1 (QCD only) | $\alpha_{ew}\alpha_s^2$ | 1.53 | 2.08 |
| cross-terms of Fig. 1 (a,b)) | $\alpha_{ew}\alpha_s^3$ | $5.32 \times 10^{-2}(+3.5\%)$ | $6.98 \times 10^{-3}(+0.34\%)$ |
| Fig. 2(c) | $\alpha_{ew}V_{cb}^4$ | $2.58 \times 10^{-7}(+0.0\%)$ | $2.67 \times 10^{-7}(+0.0\%)$ |
| Fig. 2(d) | $\alpha_{ew}^3$ | $1.65 \times 10^{-3}(+0.11\%)$ | $1.67 \times 10^{-3}(+0.08\%)$ |
| cross-terms of Fig. 1 (c,d)) | — | $-5.69 \times 10^{-4}(-0.037\%)$ | $8.23 \times 10^{-6}(+0.0\%)$ |

Now, let’s discuss the uncalculated corrections of order-$v^2$, order-$\alpha_s^3$ and order-$v^2\alpha_s^3$, where $v$ is the heavy quark or anti-quark velocity in the bound state rest frame. Generally, $v^2 \sim 25\%$ for $J/\psi$ and $v^2 \sim 10\%$ for $\Upsilon$. Assuming $v^2 \sim 20\%$ for $B_c^{(*)}$ and $\alpha_s(2m_b) \sim 0.2$, we estimate the order-$v^2$ correction to be 20%, order-$\alpha_s^3$ correction to be 20% and order-$v^2\alpha_s^3$ correction to be 4%. In fact, we calculated the order-$\alpha_s^3$ contribution from the triangle loop (top quark only) Feynman diagrams in Fig. 2(a,b), whose correction to the decay widths $\Gamma(H^0 \rightarrow B_c^{(*)} + \bar{c} + b)$ is presented in Table IV. Where percentages in the brackets are the ratios of various corrections relative to the Fig. 1 (QCD only) one. It is found that correction raised from the triangle top quark loop for $B_c$ case is bigger by a factor of 10 than that for $B_c^*$ one. Corrections through the propagation of Higgs fragments to double W/Z bosons (Fig. 2(c,d)) are also included, all of which are quite small.

Assuming that the vector state $B_c^*$ decays to the ground state $B_c$ with 100% efficiency through electromagnetic interaction, then at $\alpha_s(2m_b) = 0.214$ we have the total decay width (Since the corrections listed in Table IV are small, data in Table I are used only.):

$$\Gamma_{total}(H^0 \rightarrow B_c + \bar{c} + b) = 3.57_{-0.67}^{+0.88} KeV,$$

where the errors are caused by varying $m_c$ only, which should be the biggest uncertainty

1 This seems strange but we checked the calculation carefully.
source (as high as 25% correction). If we adopt the Higgs total decay width \( \Gamma_H = 4.20 \text{ MeV} \) \[37\], then we obtain the total branching fraction:

\[
Br_{\text{total}}(H^0 \rightarrow B_c + \bar{c} + b) = \frac{\Gamma_{\text{total}}(H^0 \rightarrow B_c + \bar{c} + b)}{\Gamma_H} \\
= 8.50(^{+1.6}_{-2.1}) \times 10^{-4}. \tag{10}
\]

Presently experimental results on Higgs couplings have no deviation from the Standard Model predictions \[3–7\], yet the new physics might lie in the Yukawa coupling highly possible. Presumably, the total branching fraction \( Br_{\text{total}} \) has a strong dependence only on the \( Hb\bar{b} \) coupling\(^2\). Given a adjustable factor \( \kappa_b \) to the \( Hb\bar{b} \) coupling, we obtain a \( \kappa_b^2 \) factor to the total branching fraction. For example, 300% correction \( (\kappa_b^2 = 4) \) to the total branching fraction implies a 100% deviation from the Standard Model \( Hb\bar{b} \) coupling. In addition, new heavier particles which couple to Higgs boson could give an appreciable enhancement to the triangle loop in Fig. 2(a,b), and/or to the coupling similar to the ones in Fig. 2(c,d) if the new particles interact with gluons and quarks.

Running at \( \sqrt{s} = 14 \text{ TeV} \) and with the integrated luminosity of \( 3 \text{ ab}^{-1} \), HL-LHC could produce \( 1.65 \times 10^8 \) Higgs boson. Hence we can obtain about \( 1.4 \times 10^5 B_c \) events according to Eq. (10). For the \( B_c \) detection, the fully constructed channel is \( B_c \rightarrow J/\psi(1S)\pi^+ \), whose branching fraction is about 0.5% \[38\]. Further considering that the branching rate of \( J/\psi \rightarrow l^+l^- (l = e, \mu) \) is about 12% \[36\], number of \( B_c \) candidates produced in Higgs decays at HL-LHC is about 80. When center-of-mass energy is upgraded to 33 TeV (i.e. at HE-LHC), the \( B_c \) events produced would be approaching 300. Then it might be a choice for experimental physicists to study the couplings of Higgs and heavy quarks through the Higgs decays to \( B_c \) channel.

To make our analysis more helpful to the experiments detection, the differential distributions of invariant masses \( s_1 = (p_0 + p_5)^2 \) and \( s_2 = (p_5 + p_6)^2 \), i.e. \( d\Gamma / ds_1 \) and \( d\Gamma / ds_2 \) are presented in Fig. 3. And the differential distributions \( d\Gamma / d\cos\theta_{12} \) and \( d\Gamma / d\cos\theta_{13} \) are displayed in Fig. 4, where \( \theta_{12} \) is the angle between \( \vec{p}_5 \) and \( \vec{p}_6 \), and \( \theta_{13} \) is that between \( \vec{p}_6 \) and \( \vec{p}_0 \) in the Higgs boson rest frame. It can be found that the largest differential width is achieved when \( B_c^{(*)} \) mesons and \( \bar{c} \) quark fly side by side \( (\theta_{12} = 0) \), or \( B_c^{(*)} \) mesons and \( b \) quark fly back to back \( (\theta_{13} = \pi) \). Here is the reason:

\(^2\) This is reasonable since the contributions from the triangle top quark loop and other couplings \( (Hc\bar{c}, HZZ \text{ and } HWW) \) are relatively small, see Tables IV, V.
FIG. 3: Differential decay widths $d\Gamma/ds_1$ (left) and $d\Gamma/ds_2$ (right) for processes $H^0(k) \rightarrow B_c^*(p_0) + \bar{c}(p_5) + b(p_6)$, where $s_1 = (p_0 + p_5)^2$ and $s_2 = (p_5 + p_6)^2$ are the invariant masses.

FIG. 4: Differential decay widths $d\Gamma/d\cos\theta_{12}$ (left) and $d\Gamma/d\cos\theta_{13}$ (right) for processes $H^0(k) \rightarrow B_c^*(p_0) + \bar{c}(p_5) + b(p_6)$, where $\theta_{12}(\theta_{13})$ is the angle between $\vec{p}_0$ and $\vec{p}_5(\vec{p}_6)$ in the Higgs boson rest frame.

- firstly, Feynman diagrams (2) and (4) in Fig. 1 (i.e. the $Hb\bar{b}$ coupling one) dominate the processes;
- then, the gluon propagator $\frac{1}{(p_3+p_5)^2}$ in $M_{2,4}^c(n)$ reaches its peak value when $B_c^*(p_0)$ mesons (in fact, the constitute quark $c(p_3)$) and $\bar{c}(p_5)$ quark go to the same direction.

Now, we will compare our results with the fragmentation ones. To make it more clear, we divide our complete NRQCD leading-order results into three groups (only QCD contributions are included here): contributions from $Hb\bar{b}$ coupling (diagrams (2,4) in Fig. 1); contributions from $Hc\bar{c}$ coupling (diagrams (1,3) in Fig. 1); the cross-terms of the previous two groups. The corresponding branching fractions are displayed in Table V where the percentages in brackets are ratios of the contributions from the three groups relative to the total branching fractions. Obviously, the contribution from $Hb\bar{b}$ coupling dominates the processes, about two orders of magnitude bigger than the $Hc\bar{c}$ one.
TABLE V: Branching fractions of \( H^0(k) \to B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_0) \) through complete leading-order NRQCD calculation (QCD contributions only). The percentages in brackets are ratios of the contributions from the three groups relative to the total branching fractions.

| Branching Fractions | \( B_c \) | \( B_c^* \) |
|---------------------|---------|---------|
| \( Hb\bar{b} \) coupling | \( 3.61 \times 10^{-4} +98.9\% \) | \( 4.97 \times 10^{-4} +100.2\% \) |
| \( Hc\bar{c} \) coupling | \( 8.82 \times 10^{-7} +0.2\% \) | \( 7.32 \times 10^{-7} +0.2\% \) |
| Cross-terms | \( 3.34 \times 10^{-6} +0.9\% \) | \( -1.85 \times 10^{-6} -0.4\% \) |

TABLE VI: Branching fractions of \( H^0 \to B_c^{(*)} \) through \( \bar{b} \) and \( c \) quark fragmentation calculation.

| Branching Fractions | \( B_c \) | \( B_c^* \) |
|---------------------|---------|---------|
| \( H^0 \to \bar{b}b \to B_c^{(*)} \) | \( 3.10 \times 10^{-4} \) | \( 4.36 \times 10^{-4} \) |
| \( H^0 \to c\bar{c} \to B_c^{(*)} \) | \( 2.00 \times 10^{-7} \) | \( 1.73 \times 10^{-7} \) |

Under the fragmentation calculation, the branching fractions can be obtained by Higgs boson decays to \( \bar{b}b \) or \( c\bar{c} \), following the \( \bar{b} \) or \( c \) quark fragments to \( B_c^{(*)} \) mesons. At \( m_H = 125.7 GeV \), the decay rates of \( H^0 \to \bar{b}b \) and \( H^0 \to c\bar{c} \) are 56.6\% and 2.85\% respectively [37]. As for the fragmentation probabilities of \( \bar{b}/c \to B_c^{(*)} \), by adopting the Eq.s (13-16) in Ref. [39] but our input parameters, we obtain the probabilities:

\[
P_{\bar{b} \to B_c} = 5.48 \times 10^{-4}, \\
P_{\bar{b} \to B_c^*} = 7.70 \times 10^{-4}, \\
P_{c \to B_c} = 7.02 \times 10^{-6}, \\
P_{c \to B_c^*} = 6.06 \times 10^{-6}.
\]  

When multiplying these fragmentation probabilities by the decay rates of Higgs decays to \( \bar{b}b/c\bar{c} \) couples, the branching fractions of \( H^0 \to B_c^{(*)} \) can be obtained directly, which are presented in Table VI. It is found that the fragmentation results consist with the complete
leading-order calculation well$^3$.

Finally, let’s take a look at the branching fractions of Higgs boson decays to charmonium and bottomonium. Within complete leading-order calculation, we obtain the branching fractions of $H^0 \to (\eta_c, J/\psi) + \bar{c} + c$ and $H^0 \to (\eta_b, \Upsilon) + \bar{b} + b$ channels as follows (only QCD contributions are included):

$$
Br(H^0 \to \eta_c + \bar{c} + c) = 7.87 \times 10^{-5},
$$
$$
Br(H^0 \to J/\psi + \bar{c} + c) = 7.59 \times 10^{-5},
$$
$$
Br(H^0 \to \eta_b + \bar{b} + b) = 8.89 \times 10^{-5},
$$
$$
Br(H^0 \to \Upsilon + \bar{b} + b) = 6.61 \times 10^{-5}.
$$

(12)

Which are about a factor of 1/5 smaller than the $B_c$ one. Consistent results can also be obtained via the fragmentation calculation (fragmentation probabilities of $b/c$ quarks fragment into quarkonia can be found in Ref. [40]). It is worth noting that a factor 2 should be multiplied since both the quark and anti-quark can fragment into the quarkonia. The $Hb\bar{b}$ coupling, which appears in Higgs decays to $B^{(*)}_c$, is about 10 times larger than the $Hc\bar{c}$ coupling, which appears in the Higgs decays to charmonium. Hence, the Higgs branching fraction to $B^{(*)}_c$ is larger than the Higgs branching fraction to charmonium. The propagator $\frac{1}{(p_3 + p_5)^2}$ in $M_{2A}^2(n)$ peaks at much larger values when the gluon fragments to $c\bar{c}$ than when it fragments to $b\bar{b}$. This effect accounts for the enhancement of the Higgs branching fraction to $B^{(*)}_c$ relative to the Higgs branching fraction to bottomonium.

In contrast to the exclusive radiative Higgs decay processes $H^0 \to (J/\psi, \Upsilon(nS)) + \gamma$, we find that the branching fractions of $H^0 \to B^{(*)}_c + \bar{c} + b$ are even larger. Latest results for $H^0 \to (J/\psi, \Upsilon(nS)) + \gamma$ can be found in Ref. [14], where direct amplitudes are evaluated at next-to-leading order in $\alpha_s$ and loop-induced indirect amplitudes are also included. The branching fractions obtained there are $\sim 10^{-6}$ for $J/\psi$ and $\sim 10^{-9}$ for $\Upsilon(nS)$, which are two and five orders of magnitude smaller than the $B^{(*)}_c$ one respectively.

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$^3$In fact, the results related to $Hb\bar{b}$ coupling agree under the two framework, yet fragmentation results related to $Hc\bar{c}$ coupling deviate by a factor of 4 from the complete leading-order calculation. We believe that the non-relativistic assumption ($v \simeq 0$) is not an apposite one when $c$ quark propagator is involved since $c$ quark is not heavy enough in the bound state. Although both framework have adopted the assumption, it might enlarge the differences of those two calculation methods when $c$ quark propagator emerges. We guess that the higher order correction in $v$ might reduce the discrepancy here. Luckily, the contribution containing the $Hc\bar{c}$ coupling is small in comparison with the $Hb\bar{b}$ coupling one here.
IV. SUMMARY AND CONCLUSIONS

In this work, we calculate the leading-order decay widths of processes $H^0 \rightarrow B^*_c + \bar{c} + b$ under NRQCD formulism, which include both QCD and QED contributions. Corrections from triangle top quark loop and $HWW$ ($HZZ$) couplings are also discussed. Uncertainties of the widths caused by the matrix elements $\langle O[n] \rangle$, quark masses and running coupling constant $\alpha_s(\mu)$ are taken into consideration. We also estimate the total branching fractions of $B^*_c$ mesons in Higgs boson decays, as well as the events at HL/HE-LHC. Effects on the total branching fraction when the $Hb\bar{b}$ coupling deviates from the Standard Model is discussed. To make the analysis more helpful, the differential distributions $d\Gamma/ds_{1,2}$ and $d\Gamma/d\cos\theta_{12,13}$ are presented. Moreover, a comparison between our results and the ones calculated under fragmentation formulism is displayed in detail. And the comparison between the branching fractions of Higgs boson decays to $B^*_c$ and those of Higgs decays to charmonium ($\eta_c, J/\psi$) or bottomonium ($\eta_b, \Upsilon$) is also presented.

We find that QCD contribution dominates the processes as is expected, and the varying $c$ quark mass has a strong influence on the total branching fraction (the correction to the total branching rates can reach about 25%). We also find that Feynman diagrams with the coupling of $Hb\bar{b}$ (i.e., Fig.1(2,4)) dominate, contributions from the triangle top quark loop and other couplings ($Hc\bar{c}$, $HWW$ and $HZZ$) are small comparatively. Differential distributions $d\Gamma/d\cos\theta_{12,13}$ show that the largest differential width emerges when $B^*_c$ mesons and $\bar{c}$ jet fly side by side, or $B^*_c$ mesons and $b$ jet fly back to back at the Higgs boson rest frame. Moreover, the calculation results inform that the branching fractions of Higgs boson decays to $B^*_c$ are bigger than those of Higgs decays to quarkonia.

According to our study, when 14 TeV LHC delivering the integrated luminosity of 3 $ab^{-1}$ (i.e. HL-LHC), about $1.4 \times 10^5$ $B_c$ events can be produced through Higgs boson decays. Considering that the detection efficiency of fully constructed channel $B_c \rightarrow J/\psi(\rightarrow l^+l^-) + \pi^+$ is around six in ten thousands, about 84 $B_c$ candidates can be observed at HL-LHC, and 3.5 times bigger when the center-of-mass energy is upgraded to 33 TeV (i.e. HE-LHC).

As a final remark, the study of $B_c$ production in Higgs boson decays could be considered as the choice for the measurement of $Hb\bar{b}$ coupling at future HL/HE-LHC. And it is also a place searching for signals which deviate from the Standard Model.
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