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Uncertainties in estimating the indirect production of B_c and its excited states via top quark decays at CERN LHC

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ABSTRACT

Main theoretical uncertainties in estimating the indirect production of $(b\bar{c})$-quarkonium (B_c^- meson and its excited states) via top quark decays, $t \to (b\bar{c}) + c + W^+$, are studied within the non-relativistic QCD framework. It is found that the dimensionless reduced decay width for a particular $(b\bar{c})$-quarkonium state, $\bar{\Gamma}_n = \Gamma_n/\Gamma_{t\to W^+ + b}$, is very sensitive to the c-quark mass, while the uncertainties from the b-quark and t-quark masses are small, where n stands for the eight $(b\bar{c})$-quarkonium states up to $\mathcal{O}(v^4)$: $|(b\bar{c})(^1S_0)_1\rangle$, $|(b\bar{c})(^3S_1)_1\rangle$, $|(b\bar{c})(^1P_1)_1\rangle$, $|(b\bar{c})(^3P_J)_1\rangle$ (with $J = (1,2,3)$), $|(b\bar{c})(^1S_0)_8 g\rangle$ and $|(b\bar{c})(^3S_1)_8 g\rangle$ respectively. About 10^8 $t\bar{t}$-pairs shall be produced per year at CERN LHC, if adopting the assumption that all the higher Fock states decay to the ground state with 100% probability, then we shall have $(1.038^{+1.353}_{-0.782}) \times 10^5$ B_c^- events per year. So the indirect production provides another important way to study the properties of B_c^- meson in comparison to that of the direct hadronic production at CERN LHC.

1. Introduction

The B_c meson is a double heavy quark–antiquark bound state and carries flavors explicitly, which provides a good platform for a systematic studies of the b or c quark decays. Since its first discovery at TEVATRON by CDF Collaboration [1], B_c physics is attracting more and wide interests. Many progresses have been made for the direct hadronic production of B_c meson at high energy colliders [2], especially, a computer program BCVEGPY for generating the B_c events has been completed in Refs. [3–5] and has been accepted by several experimental groups to simulate the B_c events. It has been estimated with the help of BCVEGPY that about 10^4 B_c events are expected to be recorded during the first year of the CMS running with a lepton trigger [6], and there are about 10^4 B_c events with $B_c \to J/\Psi + \pi$ decays in three years of ATLAS running [7].

On the other hand, the indirect production of B_c^+ or B_c^-, including its excited states, via $\bar{t}$-decay or t-decay may also provide useful knowledge of these mesons. Without confusing and for simplifying the statements, later on we will not distinguish B_c^+ and B_c^- (simply call them as B_c) and all results for B_c^+ and B_c^- obtained in the Letter are symmetric in the interchange from particle to anti-particle. With a predicted cross section for top quark pair production hundred times larger than at TEVATRON and a much higher designed luminosity, e.g. it is expected that at CERN LHC $\sim 10^8$ $t\bar{t}$-pairs can be produced per year under the luminosity $L = 10^{34}\ \mathrm{cm^{-2}\,s^{-1}}$ [8], the LHC is poised to become a "top factory". Therefore, the indirect production of B_c through top quark decays shall provide another important way to study the properties of B_c meson [9]. Within the non-relativistic QCD (NRQCD) framework [10], the decay channel $t \to (b\bar{c}) + c + W^+$ in leading order (LO) α_s calculation but with v^2-expansion up to v^4 has been recently calculated with the so-called 'new trace technology' [11], where $(b\bar{c})$-quarkonium is in one of the eight Fock states: the six color-singlet states $|(b\bar{c})(^1S_0)_1\rangle$, $|(b\bar{c})(^3S_1)_1\rangle$, $|(b\bar{c})(^1P_1)_1\rangle$ and $|(b\bar{c})(^3P_J)_1\rangle$ (with $J = (1,2,3)$), and two color-octet states $|(b\bar{c})(^1S_0)_8 g\rangle$ and $|(b\bar{c})(^3S_1)_8 g\rangle$ respectively. It has been argued that when $10^8 t\bar{t}$ events per year are produced at LHC, then it is possible to accumulate about 10^5 B_c events per year via t-quark decays at LHC. Thus in comparison to that of the direct hadronic production, there may be some advantages in $(b\bar{c})$-quarkonium studies via the indirect production due to the fact that the top quark events shall always be recorded at LHC.

Considering the forthcoming LHC running, and various experimental feasibility studies of B_c are in progress, it may be interesting to know the theoretical uncertainties quantitatively in estimating of B_c production. The uncertainties of the direct hadronic production of B_c through its dominant gluon–gluon fusion mechanism has been studied in Refs. [12,13], while the present Letter is served to study the uncertainties of the indirect mechanism through the decay channel $t \to (b\bar{c}) + c + W^+$. These two cases are compensate to each other and may be useful for experimental studies. At the present, we shall restrict ourselves to examine the uncertainties at the lowest order, because the next-to-leading order (NLO) calculation cannot be available soon due to its complicatedness. For definiteness, we shall examine the main uncertainties that are

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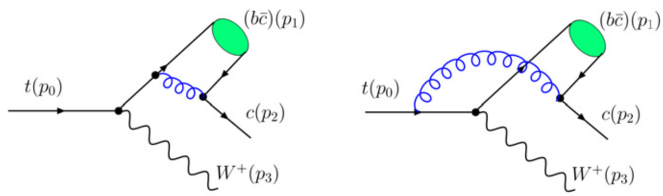

Fig. 1. Feynman diagrams for the indirect production of $(b\bar{c})$-quarkonium through top quark decays.

caused by the value of the t-quark mass, the values of the bound state parameters m_c and m_b, and the choice of the renormalization scale Q^2.

The remainder of the Letter is organized as follows. Section 2 gives the calculation technology for the indirect production of $(b\bar{c})$-quarkonium states through the top quark decays. Section 3 is devoted to present the numerical results and to discuss the corresponding uncertainties with the help of the formulae given in Ref. [11]. And Section 4 is reserved for a summary.

2. Calculation technology

Within the non-relativistic QCD (NRQCD) frame work [10], the dimensionless reduced decay width for the production of $(b\bar{c})$-quarkonium through the channel $t(p_0) \to (b\bar{c})(p_1) + c(p_2) + W^+(p_3)$ takes the following factorization form:

$$\bar{\Gamma} = \sum_n \bar{\Gamma}_n = \sum_n \left[\frac{1}{\Gamma_{t\to W^+ + b}} H_n\big(t \to (b\bar{c}) + c + W^+\big) \times \frac{\langle \mathcal{O}_n \rangle}{N_{\text{col}}} \right], \quad (1)$$

where $\bar{\Gamma}_n$ stands for the reduced decay width for a particular $(b\bar{c})$-quarkonium state, and the sum is over all the $(b\bar{c})$-quarkonium states up to $\mathcal{O}(v^4)$, which includes six color singlets $|(b\bar{c})(^1S_0)_1\rangle$, $|(b\bar{c})(^3S_1)_1\rangle$, $|(b\bar{c})(^1P_1)_1\rangle$ and $|(b\bar{c})(^3P_J)_1\rangle$ (with $J = (1, 2, 3)$), and two color octets $|(b\bar{c})(^1S_0)_8 g\rangle$ and $|(b\bar{c})(^3S_1)_8 g\rangle$ respectively. N_{col} refers to the number of colors, n stands for the involved states of $(b\bar{c})$-quarkonium. $N_{\text{col}} = 1$ for singlets and $N_{\text{col}} = N_c^2 - 1$ for octets. $\langle \mathcal{O}_n \rangle$ stands for the decay matrix element that can be related with the wave function at zero $R_S(0)$ or the derivative of the radial wave function at origin $R'_P(0)$ through the saturation approximation [10]. The overall factor $1/\Gamma_{t\to W^+ + b}$ is introduced to cut off the uncertainty from the electroweak coupling. The decay width of the two body decay process $t(p_1) \to b(p_2) + W^+(p_3)$ that is dominant for the t-quark decays can be written as

$$\Gamma_{t\to W^+ + b} = \frac{G_F m_t^2 |\vec{\mathbf{p}}_2|}{4\sqrt{2\pi}} \left[\left(1 - y^2\right)^2 + x^2\left(1 + y^2 - 2x^2\right) \right], \quad (2)$$

where $|\vec{\mathbf{p}}_2| = \frac{m_t}{2}\sqrt{(1 - (x - y)^2)(1 - (x + y)^2)}$, $x = m_w/m_t$ and $y = m_b/m_t$.

As shown in Fig. 1, there are two Feynman diagrams for the concerned process $t(p_0) \to (b\bar{c})(p_1) + c(p_2) + W^+(p_3)$. Due to the involved massive quarks, the calculation of the process is very complicated and lengthy, to simplify the calculation, we have improved a so-called 'new trace technology' to calculate the process [11]. Under such approach, we first arrange the whole amplitude into several orthogonal sub-amplitudes $M_{ss'}$ according to the spins of the t-quark (s') and c-quark (s), and then do the trace of the Dirac γ matrix strings at the amplitude level by properly dealing with the massive spinors, which results in explicit series over some independent Lorentz-structures, and finally, we obtain the square of the amplitude. All the necessary formulae together with its subtle points for the square of the hard scattering amplitude $H_n(t \to (b\bar{c}) + c + W^+)$ can be found in Ref. [11], so we shall only present the main results here and the interesting reader may turn to Ref. [11] for more detailed calculation technology.

The involved color-singlet and color-octet matrix elements provide systematical errors for the NRQCD framework itself. Their values can be determined by global fitting of the experimental data or directly related to the wave functions at the zero point $R_S(0)$ (or the derivative of the wave function at the zero point $R'_P(0)$) derived from certain potential models for the color-singlet case, some potential models can be found in Refs. [14–17]. A model dependent analysis of $R_S(0)$ and $R'_P(0)$ can be found in Ref. [18], where the spectrum of B_c under the Cornell potential [14], the Buchmüller–Tye potential [15], the power-law potential [16] and the logarithmic potential [17] have been discussed respectively in their discussions, which shows that $|R_S(0)|^2 \in [1.508, 1.710]\ \text{GeV}^3$ and $|R'_P(0)|^2 \in [0.201, 0.327]\ \text{GeV}^5$.[1] Since the model-dependent $R_S(0)$ and $R'_P(0)$ emerge as overall factors and their uncertainties can be conveniently discussed when we know their possible ranges well, so we shall not discuss such uncertainties in the present Letter. More explicitly, we shall fix their values to be: $|R_S(0)|^2 = 1.642\ \text{GeV}^3$ and $|R'_P(0)|^2 = 0.201\ \text{GeV}^5$, which is derived under the Buchmüller–Tye potential [18]. Secondly, although we do not know the exact values of the two decay color-octet matrix elements, $\langle b\bar{c}(^1S_0)_8|\mathcal{O}_8(^1S_0)|b\bar{c}(^1S_0)_8\rangle$ and $\langle b\bar{c}(^3S_1)_8|\mathcal{O}_8(^3S_1)|b\bar{c}(^3S_1)_8\rangle$, we know that they are one order in v^2 higher than the S-wave color-singlet matrix elements according to NRQCD scale rule. More specifically, based on the velocity scale rule [10], we have

$$\begin{aligned}&\langle b\bar{c}(^1S_0)_8 | \mathcal{O}_8(^1S_0) | b\bar{c}(^1S_0)_8 \rangle \\ &\quad \simeq \Delta_S(v)^2 \cdot \langle b\bar{c}(^1S_0)_1 | \mathcal{O}_1(^1S_0) | b\bar{c}(^1S_0)_1 \rangle \end{aligned} \quad (3)$$

and

$$\begin{aligned}&\langle b\bar{c}(^3S_1)_8 | \mathcal{O}_8(^3S_1) | b\bar{c}(^3S_1)_8 \rangle \\ &\quad \simeq \Delta_S(v)^2 \cdot \langle b\bar{c}(^3S_1)_1 | \mathcal{O}_1(^3S_1) | b\bar{c}(^3S_1)_1 \rangle, \end{aligned} \quad (4)$$

where the second equation comes from the vacuum-saturation approximation. $\Delta_S(v)$ is of order v^2 or so, and we take it to be within the region of 0.10–0.30, which is in consistent with the identification: $\Delta_S(v) \sim \alpha_s(Mv)$ and has covered the possible variation due to the different ways to obtain the wave functions at the origin (S-wave) and the first derivative of the wave functions at the origin (P-wave), etc.

In addition to the color-singlet and color-octet matrix elements, the quark mass values m_t, m_c and m_b also 'generate' uncertainties for the hadronic production. At present, these parameters cannot be completely fixed by fitting the available data of the heavy quarkonium. Furthermore, since the $(b\bar{c})$-quarkonium state is the non-relativistic and weak-binding bound state, we approximately have $M_{B_c} = m_b + m_c$, which also is the requirement from the gauge invariance of the hard scattering amplitude.

To choose the renormalization scale Q^2 is a tricky problem for the estimates of the LO pQCD calculation. If Q^2 is chosen properly, the results may be quite accurate. In the present case with three-body final state, there is ambiguity in choosing the renormalization scale Q^2 and various choices of Q^2 would generate quite different results. Such kind of ambiguity cannot be justified by the LO calculation itself, so we take it as the uncertainty of the LO calculation, although when the NLO calculation of the subprocess is available, the uncertainty will become under control a lot. While the NLO calculation is very complicated and it cannot be available in the foreseeable future, so here we take Q^2 as the possible characteristic momentum of the hard subprocess being squared. According to the factorization formulae, the running of α_s should be of leading logarithm order, and the energy scale Q^2 appearing in the

[1] Since the Cornell potential has stronger singularity in spatially smaller states [18], so we do not include its corresponding values for $R_S(0)$ and $R'_P(0)$.