Bc Meson Indirect Production via Anti t-quark Decay

Chao-Hsi Chang (Zhao-Xi Zhang )
I.T.P., Chinese Academy of Sciences

1. Introduction
   Why ? we are interested in indirect production
   Bc excited states are included

2. Formulation & Numerical Results
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Why? Indirect Production via anti t-quark Decay

• At High Luminosity Runs

ATLAS & CMS focus on new physics, their trigger conditions are set $P_T$ very high.

The direct production of $B_c$ ($B_c^*$) meson decreases with $P_T$ quickly

AT LHC

Thus in ATLAS & CMS Exp. the direct production is suppressed greatly.

• The mechanism (indirect production of $B_c$ via anti t-quark decay)

The produced $B_c$ mesons may survive from the ATLAS & CMS Exp. Trigger.
Why? Indirect Production via anti t-quark Decay

The cross section of $t \bar{t}$ pair production at LHC is quite greater: $10^7 \sim 10^8$ $t \bar{t}$ pairs/year ($\mathcal{L}=10^{34}$cm$^{-2}$s$^{-1}$)

According to SM:

$$\Gamma_{t \rightarrow b_+W^+} = 1.59\text{GeV}$$

and

$$Br(t \rightarrow b + W^+) \simeq 1.0$$

Moreover the Bc and its excited states produced indirectly may gain a great $P_T$ due to heavy t-quark mass.

• **Theoretical interests:** more mechanisms may test the NRQCD framework more (as compensations to known ones).
Formulation & Numerical results

Let us estimate \[ \Gamma_{t \to B_\bar{c}}(\bar{B}_\bar{c}^*, \ldots) + W^+ = ? \]

Define: \( s_1 = (p_1 + p_2)^2 \)
\( s_2 = (p_2 + p_3)^2 \)

NRQCD framework:

\[
\Gamma = \sum_n H_n(t \to (b\bar{c}) + c + W^+) \times \frac{\langle \mathcal{O}_n \rangle}{N_{col}}
\]

\( N_{col} \) refers to the number of colors
\( n \) stands for the involved state of \( b\bar{c} \)-quarkonium

\( N_{col} = 1 \) for singlets \& \( N_{col} = N_c^2 - 1 \) for octets

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According to the Feynman diagrams, for S=0, L=0 (Bc meson):

\[
\mathcal{A}_{1}^{S=0,L=0} = iC\bar{u}_i(p_2, s)\left[\gamma_\mu \frac{\Pi_0^{P_1}(q)}{(p_2 + p_{11})^2} \gamma_\mu \frac{\slashed{p}_1 + \slashed{p}_2 + m_b}{(p_1 + p_2)^2 - m_b^2} \gamma_\mu (p_3)P_L \right]u_j(p_0, s')|_{q=0},
\]

\[
\mathcal{A}_{2}^{S=0,L=0} = iC\bar{u}_i(p_2, s)\left[\gamma_\mu \frac{\Pi_0^{P_1}(q)}{(p_2 + p_{11})^2} \gamma_\mu (p_3)P_L \frac{\slashed{p}_{12} + \slashed{p}_3 + m_t}{(p_{12} + p_3)^2 - m_t^2} \right]u_j(p_0, s')|_{q=0}
\]

for S=1, L=0 (Bc* meson)

\[
\mathcal{A}_{1}^{S=1,L=0} = iC\bar{u}_i(p_2, s)\left[\gamma_\mu \frac{\epsilon_\alpha^s(p_1)\Pi_\alpha^{P_1}(q)}{(p_2 + p_{11})^2} \gamma_\mu \frac{\slashed{p}_1 + \slashed{p}_2 + m_b}{(p_1 + p_2)^2 - m_b^2} \gamma_\mu (p_3)P_L \right]u_j(p_0, s')|_{q=0},
\]

\[
\mathcal{A}_{2}^{S=1,L=0} = iC\bar{u}_i(p_2, s)\left[\gamma_\mu \frac{\epsilon_\alpha^s(p_1)\Pi_\alpha^{P_1}(q)}{(p_2 + p_{11})^2} \gamma_\mu (p_3)P_L \frac{\slashed{p}_{12} + \slashed{p}_3 + m_t}{(p_{12} + p_3)^2 - m_t^2} \gamma_\mu \right]u_j(p_0, s')|_{q=0}
\]
Formulation & Numerical results

for $S=0$, $L=1$ ($h_{BC}$ meson):

$$A_{1}^{S=0,L=1} = iC\varepsilon_{i}^{\alpha}(p_{1})\bar{u}_{i}(p_{2}, s) \frac{d}{dq_{\alpha}} \left[ \gamma_{\mu} \frac{\Pi_{p_{1}}^{0}(q)}{(p_{2} + p_{1})^{2}} \gamma_{\mu} \frac{\not{p}_{1} + \not{p}_{2} + m_{b}}{(p_{1} + p_{2})^{2} - m_{b}^{2}} \gamma_{\mu}^{\not{q}_{3}} P_{L} \right] u_{j}(p_{0}, s') |_{q=0}$$

$$A_{2}^{S=0,L=1} = iC\varepsilon_{i}^{\alpha}(p_{1})\bar{u}_{i}(p_{2}, s) \frac{d}{dq_{\alpha}} \left[ \gamma_{\mu} \frac{\Pi_{p_{1}}^{0}(q)}{(p_{2} + p_{1})^{2}} \gamma_{\mu}^{\not{q}_{3}} P_{L} \frac{\not{p}_{12} + \not{p}_{3} + m_{t}}{(p_{12} + p_{3})^{2} - m_{t}^{2}} \gamma_{\mu} \right] u_{j}(p_{0}, s') |_{q=0}$$

for $S=1$, $L=1$ ($\chi^{J=0,1,2}_{BC}$ meson):

$$A_{1}^{S=1,L=1} = iC\varepsilon_{\alpha\beta}(p_{1})\bar{u}_{\alpha}(p_{2}, s) \frac{d}{dq_{\alpha}} \left[ \gamma_{\mu} \frac{\Pi_{p_{1}}^{1}(q)}{(p_{2} + p_{1})^{2}} \gamma_{\mu} \frac{\not{p}_{1} + \not{p}_{2} + m_{b}}{(p_{1} + p_{2})^{2} - m_{b}^{2}} \gamma_{\mu}^{\not{q}_{3}} P_{L} \right] u_{j}(p_{0}, s') |_{q=0}$$

$$A_{2}^{S=1,L=1} = iC\varepsilon_{\alpha\beta}(p_{1})\bar{u}_{\alpha}(p_{2}, s) \frac{d}{dq_{\alpha}} \left[ \gamma_{\mu} \frac{\Pi_{p_{1}}^{1}(q)}{(p_{2} + p_{1})^{2}} \gamma_{\mu}^{\not{q}_{3}} P_{L} \frac{\not{p}_{12} + \not{p}_{3} + m_{t}}{(p_{12} + p_{3})^{2} - m_{t}^{2}} \gamma_{\mu} \right] u_{j}(p_{0}, s') |_{q=0}$$

Note: the color factor is taken account by $C$. 

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Formulation & Numerical results

Fock states velocity scaling rule:

\[ |\bar{B}_c\rangle = \mathcal{O}(v^0)|(b\bar{c})_1(1S_0)\rangle + \mathcal{O}(v^2)|(b\bar{c})_8(1P_1)g\rangle + \cdots \]
\[ |\bar{B}_c^*\rangle = \mathcal{O}(v^0)|(b\bar{c})_1(3S_1)\rangle + \mathcal{O}(v^2)|(b\bar{c})_8(3P_J)g\rangle + \cdots \]
\[ |h_{B_c}\rangle = \mathcal{O}(v^0)|(b\bar{c})_1(1P_1)\rangle + \mathcal{O}(v^1)|(b\bar{c})_8(1S_0)g\rangle + \cdots \]
\[ |\chi_{B_c}^J\rangle = \mathcal{O}(v^0)|(b\bar{c})_1(3P_J)\rangle + \mathcal{O}(v^1)|(b\bar{c})_8(3S_1)g\rangle + \cdots \]

Roughly \[ v^2 \simeq 0.1 \sim 0.3 \]

Matrix elements as NRQCD (with \( T^{(ij)} = (T_{ij} + T_{ji})/2 - T_{kk}\delta_{ij} \)):

\[ \langle b\bar{c}(1S_0)_{1}|\mathcal{O}_1(1S_0)b\bar{c}(1S_0)_{1}\rangle = \frac{1}{\sqrt{2N_c}}\langle 0|\chi_c^+\psi_b|b\bar{c}(1S_0)_{1}\rangle^2[1 + \mathcal{O}(v^4)], \]
\[ \langle b\bar{c}(3S_1)_{1}|\mathcal{O}_1(3S_1)b\bar{c}(3S_1)_{1}\rangle = \frac{1}{\sqrt{2N_c}}\langle 0|\chi_c^+\sigma\psi_b|b\bar{c}(3S_1)_{1}\rangle^2[1 + \mathcal{O}(v^4)], \]
\[ \langle b\bar{c}(1P_1)_{1}|\mathcal{O}_1(1P_1)b\bar{c}(1P_1)_{1}\rangle = \frac{1}{\sqrt{2N_c}}\langle 0|\chi_c^+(-\frac{i}{2}\bar{D})\psi_b|b\bar{c}(1P_1)_{1}\rangle^2[1 + \mathcal{O}(v^4)], \]
\[ \langle b\bar{c}(3P_0)_{1}|\mathcal{O}_1(3P_0)b\bar{c}(3P_0)_{1}\rangle = \frac{1}{\sqrt{3\sqrt{2N_c}}}\langle 0|\chi_c^+(-\frac{i}{\sqrt{2}}\bar{D} \cdot \sigma)\psi_b|b\bar{c}(3P_0)_{1}\rangle^2[1 + \mathcal{O}(v^4)], \]
\[ \langle b\bar{c}(3P_1)_{1}|\mathcal{O}_1(3P_1)b\bar{c}(3P_1)_{1}\rangle = \frac{1}{\sqrt{2\sqrt{2N_c}}}\langle 0|\chi_c^+(-\frac{i}{\sqrt{2}}\bar{D} \times \sigma)\psi_b|b\bar{c}(3P_1)_{1}\rangle^2[1 + \mathcal{O}(v^4)], \]
\[ \langle b\bar{c}(3P_2)_{1}|\mathcal{O}_1(3P_2)b\bar{c}(3P_2)_{1}\rangle = \frac{1}{\sqrt{2N_c}}\langle 0|\chi_c^+(-\frac{i}{2}\bar{D}^{(i)}\sigma^{(j)})\psi_b|b\bar{c}(3P_2)_{1}\rangle^2[1 + \mathcal{O}(v^4)], \]
Formulation & Numerical results

\[ p_{11} = \frac{m_c}{M} p_1 + q \quad \text{and} \quad p_{12} = \frac{m_b}{M} p_2 - q \]

Project operators:

\[ \Pi_{p_1}^0 (q) = \frac{-\sqrt{M}}{4m_b m_c} (\phi_{11} - m_c) \gamma_5 (\phi_{12} + m_b) \]

\[ \Pi_{p_1}^\alpha (q) = \frac{-\sqrt{M}}{4m_+ m_-} (\phi_{11} - m_c) \gamma^\alpha (\phi_{12} + m_b) \]

\[ \frac{d}{dq_\alpha} \Pi_{p_1}^0 (q) |_{q=0} = \frac{\sqrt{M}}{4m_b m_c} \gamma_5 \gamma_\alpha (\phi_1 + m_b - m_c) \]

\[ \frac{d}{dq_\alpha} \Pi_{p_1}^\beta (q) |_{q=0} = -\frac{\sqrt{M}}{4m_b m_c} [\gamma_\alpha \gamma_\beta (\phi_1 + m_b - m_c) \]

\[ -2 \gamma_\alpha \gamma_\beta (\phi_{11} - m_c) \].

Here \( p_{i_1}^0 \gamma^{\alpha} = 0, \ p_{i_1}^{\alpha} \gamma^{\alpha \beta} = p_{i_1}^{\beta} \gamma^{\alpha \beta} = 0; \ p_{i_1}^0 = \frac{m_c}{M} p_1 \ p_{i_2}^0 = \frac{m_b}{M} p_2 \) are applied.
Formulation & Numerical results

With definition $\Pi_{\alpha\beta} = -g_{\alpha\beta} + \frac{p_{1\alpha}p_{1\beta}}{M^2}$, we have the sum for $B_c^*$ & $h_{B_c}$:

$$\sum_{J_z = s_z \text{ or } t_z} \varepsilon^{\alpha}_\alpha \varepsilon^{\ast}_{\alpha'} = \Pi_{\alpha\alpha'}$$

and the sum for $\chi_{B_c}^{J=0,1,2}$:

$$\varepsilon^{(0)}_{\alpha\beta} \varepsilon^{(0)*}_{\alpha'\beta'} = \frac{1}{3} \Pi_{\alpha\beta} \Pi_{\alpha'\beta'}$$

$$\sum_{J_z} \varepsilon^{(1)}_{\alpha\beta} \varepsilon^{(1)*}_{\alpha'\beta'} = \frac{1}{2} (\Pi_{\alpha\alpha'} \Pi_{\beta\beta'} - \Pi_{\alpha\beta'} \Pi_{\alpha'\beta})$$

$$\sum_{J_z} \varepsilon^{(2)}_{\alpha\beta} \varepsilon^{(2)*}_{\alpha'\beta'} = \frac{1}{2} (\Pi_{\alpha\alpha'} \Pi_{\beta\beta'} + \Pi_{\alpha\beta'} \Pi_{\alpha'\beta}) - \frac{1}{3} \Pi_{\alpha\beta} \Pi_{\alpha'\beta'}$$

For later comparison, the main decay for t-quark:

$$t(p_1) \rightarrow b(p_2) + W^+(p_3): \quad \Gamma = \frac{G_F m_t^2 |\mathbf{p}_2|}{4\sqrt{2\pi}} \left[ (1 - y^2)^2 + x^2 (1 + y^2 - 2x^2) \right]$$

For $m_w = m_x$, and $m_b = m_y$.

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The parameters for numerical calculations:

\[ m_b = 4.9 \text{ GeV}, \quad m_c = 1.5 \text{ GeV}, \quad m_t = 176 \text{ GeV}, \quad m_{\tau} = 80.22 \text{ GeV}. \quad \alpha_s(2m_c) = 0.26 \]

and (with \( V_{tb} \sim 1.0 \)) we have \( \Gamma(t \rightarrow W^+ + b) = 1.59 \text{GeV} \):

\[
\begin{align*}
\Gamma_{t \rightarrow (b\bar{c})[(^3S_1)_1]} &= 0.79 \text{ MeV} \\
\Gamma_{t \rightarrow (b\bar{c})[(^1S_0)_1]} &= 0.57 \text{ MeV} \\
\Gamma_{t \rightarrow (b\bar{c})[(^1P_1)_1]} &= 0.057 \text{ MeV} \\
\Gamma_{t \rightarrow (b\bar{c})[(^3P_0)_1]} &= 0.034 \text{ MeV} \\
\Gamma_{t \rightarrow (b\bar{c})[(^3P_1)_1]} &= 0.070 \text{ MeV} \\
\Gamma_{t \rightarrow (b\bar{c})[(^3P_2)_1]} &= 0.075 \text{ MeV} \\
\Gamma_{t \rightarrow (b\bar{c})[(^3S_1)\delta]} &= 0.091 \times v^4 \text{ MeV} \\
\Gamma_{t \rightarrow (b\bar{c})[(^1S_0)\delta]} &= 0.070 \times v^4 \text{ MeV}
\end{align*}
\]
Formulation & Numerical results

The Bc excited states mainly decay into the ground states via strong and/or electromagnetic interaction, the total indirect production of Bc should count all of the states (including its excited states), hence the ‘branching’ ratio to Bc should sum over all those of the production:

\[ \sum_{t\to(b\bar{c})+\cdots} \frac{\Gamma_{t\to(b\bar{c})+\cdots}}{\Gamma(t \to W^+ + b)} = \frac{\Gamma_{t\to(b\bar{c})\left[(^3S_1)\right]}}{\Gamma(t \to W^+ + b)} + \frac{\Gamma_{t\to(b\bar{c})\left[(^1S_0)\right]}}{\Gamma(t \to W^+ + b)} + \cdots = (1.0 \sim 2.0) \times 10^{-3} \]

The distribution about \( s_1 \) and \( s_2 \):

( The order (up-down): \((^3S_1)\_1, (^1S_0)\_1, (^3P_2)\_1, (^3P_1)\_1, (^1P_1)\_1, (^3P_0)\_1\) )

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The angle distribution:

(The order (up-down): \((^3S_1)_1, (^1S_0)_1, (^3P_2)_1, (^3P_1)_1, (^1P_1)_1, (^3P_0)_1\))

From the above angle distribution, we may see that the c-quark is favored to move in the same direction as the produced meson \(Bc\) but W-boson is favored to move in the opposite direction in the C.M. system of the anti t-quark.
Discussions & Suggestion

The B_c meson and its excited states produced indirectly survive from the experimental trigger conditions set by ATLAS & CMS detectors, since t-quark physics is one of their main physics goals.

• Advantages for the production from anti t-quark decay such as
  Associate with W-boson & a c-quark;
  The c-quark is favored to move in the direction of B_c meson etc that may be used to reject experimental background so as to increase the identification efficiency.
Discussions & Suggestion

- ‘Sufficient’ events \((10^7 \sim 10^8 \times \sim 10^{-3} = 10^4 \sim 10^5 \text{ events/year})\)
  - Accessible experimentally
  - Especially the possible upgrade version:
    - SLHC (ten times luminosity),
    - DLHC (double energy),
    - TLHC (trible energy)

Therefore, we strongly recommend that it is worth for while according to the detectors to simulate the production to see whether the indirect production is really accessible at ATLAS & CMS, and it indeed has the advantages at high luminosity runs in comparison with the direct production in studying \(B_c\) production mechanism and decay properties etc seriously.
Thanks