Doubly-charmed baryon production in $Z$ boson decay

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Abstract

In this paper, we carry out a detailed study of doubly-charmed baryon production in $Z$ boson decay, on the basis of the nonrelativistic QCD factorization. With the inclusion of the di-quark states $(cc)[^{3}S_{1}]_{3}$ and $(cc)[^{1}S_{0}]_{6}$, the branching ratio of $B_{Z\rightarrow \Xi_{cc}+X}$ is predicted to be of the $10^{-5}$ order, indicating its experimental measurability. By comparing to the $\Lambda_{c}^{+}$ yield in $Z$ decay, we predict $R_{\Xi_{cc}^{+}}(=\frac{\Gamma(Z\rightarrow\Xi_{cc}^{+})\times B(\Xi_{cc}^{+}\rightarrow\Lambda_{c}^{+}K^{-}\pi^{+})}{\Gamma(Z\rightarrow\Lambda_{c}^{+})}) = (0.85^{+0.10}_{-0.07}) \times 10^{-4}$ and $R_{\Xi_{cc}^{++}}(=\frac{\Gamma(Z\rightarrow\Xi_{cc}^{++})\times B(\Xi_{cc}^{++}\rightarrow\Lambda_{c}^{+}K^-\pi^{+}\pi^{+})}{\Gamma(Z\rightarrow\Lambda_{c}^{+})}) = (1.70^{+0.20}_{-0.14}) \times 10^{-4}$, which are at clear variance with the SELEX measurements but comparable with the values given by the LHCb and Belle collaborations.

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I. INTRODUCTION

The doubly-charmed baryon (labeled as Ξ_{cc}), which is assumed to contain two c quarks and a light quark q (q = u, d, s) based on the quark model [1–5], can provide unique test for the quantum chromodynamics (QCD). The past decades have seen the rapid developments of the Ξ_{cc} related studies, including both experimental and theoretical aspects.

By reconstructing Ξ_{cc}^{+} (ccu) via its decay into Λ_{c}^{+}K^{−}π^{+}, the SELEX collaboration reported a large production rate of Ξ_{cc}^{+} (i.e. \( R_{\Xi_{cc}^{+}} = \frac{\sigma(\Xi_{cc}^{+}) \times B(\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}K^{−}π^{+})}{\sigma(\Lambda_{c}^{+})} = 9\% \)) [6], which, however, was even not confirmed by the FOCUS collaboration [7] that is at the same collider of SELEX. In 2013, the LHCb Collaboration performed its first search for Ξ_{cc}^{+}, reporting the upper limit of \( R_{\Xi_{cc}^{+}} \) is from 1.5 \times 10^{-2} (corresponding to the Ξ_{cc} lifetime of 100 fs) to 3.9 \times 10^{-4} (400 fs) [8], which is recently updated to be from 6.5 \times 10^{-3} (40 fs) to 9 \times 10^{-4} (160 fs) for \( \sqrt{s} = 8 \) TeV, and from 4.5 \times 10^{-4} (40 fs) to 1.2 \times 10^{-4} (160 fs) for \( \sqrt{s} = 13 \) TeV [9]. The LHCb data appear to be at clear variance with the SELEX-measured \( R_{\Xi_{cc}^{+}} \). Comparing to Ξ_{cc}^{+}, Ξ_{cc}^{++} (uud) has a much longer lifetime and is then much easier to be tagged from the LHC background [10]. In 2017, the LHCb collaboration firstly detected the decay channel Ξ_{cc}^{++} \rightarrow \Lambda_{c}^{+}K^{−}π^{+}π^{+} with \( \Lambda_{c}^{+} \rightarrow pK^{−}π^{+} \) [11], and then observed the decay channels of Ξ_{cc}^{++} \rightarrow Ξ_{cc}^{+}π^{+} [12] and Ξ_{cc}^{++} \rightarrow Ξ_{cc}^{+}π^{+}π^{+} [13]. In 2019, LHCb achieved the first measurement of the Ξ_{cc}^{++} production in proton-proton collision [14], reporting \( R_{\Xi_{cc}^{++}} = \frac{\sigma(\Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+}K^{−}π^{+}π^{+})}{\sigma(\Lambda_{c}^{+})} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4} \). Besides the hadroproduction, the Ξ_{cc} production in e^{+}e^{-} annihilation has also been measured [15]–[17]. The upper limits of \( \sigma(e^{+}e^{-} \rightarrow Ξ_{cc}^{++} + X) \) given by the Belle collaboration are comparable with the theoretical predictions; the values of \( R_{\Xi_{cc}^{++}} \) are measured to be \( \sim 10^{-4} \).

In addition to the direct productions [18]–[54], such as the hadro-, photo-, and electroproductions, the indirect Ξ_{cc} yield in decays [55]–[58], which is indeed very complementary to the direct case, is also of great interest to study the doubly-charmed baryon. For example, Niu. et al. pointed out about \( 10^3 \) Ξ_{cc} events can be accumulated through higgs decay in one running year at the proposed HL-LHC; Li. et al. indicated the branching ratio of \( B_{\Upsilon(1S) \rightarrow Ξ_{cc} + X} \) can be significant and can be well measured as the \( \Upsilon(1S) \) decay to \( J/\psi + c + \bar{c} + X \). In addition to these decay processes, the Z boson decay could also provide a uniquely good chance for the Ξ_{cc}-related study. At the LHC, \( \sim 10^9 \) Z events are expected to be generated per year [59], which would be largely increased by the HE(L)-LHC upgrade program. The
The proposed future $e^+e^-$ collider, CEPC [60], equipped with “clean” background and enormous $Z$ production events ($\sim 10^{12}$/year), would also be beneficial to hunt $\Xi_{cc}$ yield through $Z$ decay. Thus, it appears promising to measure $Z$ decaying into inclusive $\Xi_{cc}$. Moreover, heavy-quarkonium production in $Z$ decay (such as $Z \to J/\psi + X$), which is analogue to our concerned $\Xi_{cc}$ case, has triggered increasing attentions and has accumulated abundant experimental data [61]. Taken together, we, in this paper, would perform a detailed study of $Z \to \Xi_{cc} + X$, presenting the estimations of $R_{\Xi_{cc}^{++}}$ in the course of $Z$ decay.

The rest of the paper is organized as follows: In Sec. II, we give a description on the calculation formalism. In Sec. III, the phenomenological results and discussions are presented. Section IV is reserved as a summary.

II. CALCULATION FORMALISM

A. General Formalism

The production of the doubly-charmed baryon is often assumed to be factorized into two steps [18, 28, 44]. The first procedure is to produce a $c$-quark pair ($cc)[n]$ by the perturbative calculable hard processes, with subsequent nonperturbative transition into a bounding diquark $\langle cc\rangle[n]$ that can be described by a matrix element, $h_{[n]}$. The next step is the hadronization of $\langle cc\rangle[n]$ into a physical colorless baryon $\Xi_{ccq}$ ($q = u, d, s$) by grabbing a light quark with possible soft gluons from the hadron; during the hadronization, the “direct evolution mechanism” assumes the total evolving probability to be 100%, among which the fragmentation probabilities into $\Xi_{ccu}$, $\Xi_{ccd}$, and $\Xi_{ccs}$ account for 43%, 43%, and 14%, respectively [10, 47, 62].

Within the nonrelativistic QCD (NRQCD) framework [63], the differential decay width of $Z \to \Xi_{cc} + X$ can be expressed as

$$d\Gamma = d\hat{\Gamma}_{Z \to (cc)[n] + X} \langle O_{\Xi_{cc}}(n) \rangle,$$

where $\hat{\Gamma}_{Z \to (cc)[n] + X}$ is the perturbative calculable short distance coefficients (SDCs), representing the production of a configuration of the $(cc)[n]$ intermediate state. At the leading order of $v_c$ (the relative velocity of the two constituent $c$ quarks in the diquark),\(^1\) $n$ takes on

\(^1\) The contributions of the $P$-wave processes would at least be $v_c^2$ suppressed to that of the $S$-wave processes.
either $[^3S_1]_3$ or $[^1S_0]_6$, due to the symmetry of identical particles in the diquark state. The subscripts $3(6)$ (as will be depicted in later section) denote the color state of the diquark. The universal long distance matrix element $\langle \mathcal{O} \Xi_{cc}(n) \rangle$ stands for the transition probability of the $c$-quark pair into the diquark multiplied by the subsequent fragmentation probability into $\Xi_{cc}$, i.e., $h([[^3S_1]_3][[^1S_0]_6]) \times 100\%$ based on the “direct evolution mechanism”.

B. Amplitudes

The SDCs in Eq. (1) can be written as

$$\hat{\Gamma}_{Z \to (cc)[n] + \bar{c} + \bar{c}} = |\mathcal{M}|^2 d\Phi_3,$$

where $|\mathcal{M}|^2$ and $d\Phi_3$ are the squared matrix element and the standard 3-body phase space, respectively. For $Z \to (cc)[n] + \bar{c} + \bar{c}$, there are in total 8 Feynman diagrams, half of which are shown in Fig. 1. The other 4 ones can be obtained by exchanging the two identical $c$-quark lines inside the diquark. Because we have set $v_c = 0$, the two portions of 4 diagrams contribute identically; in this case, we only need to calculate the 4 diagrams in Figure 1 and multiply a factor of $2^2$. Simultaneously we should introduce an additional factor of $1/(2!2!)$ to deal with the identities of the two constituent $c$ quarks inside the diquark and the two final-state $\bar{c}$ quarks.

$\Phi_3$

For example, the $P$-wave contributions just account for about $3\% - 5\%$ of the total cross sections of the hadroproduced $\Xi_{cc}$ \cite{4}. 

\footnote{For example, the $P$-wave contributions just account for about $3\% - 5\%$ of the total cross sections of the hadroproduced $\Xi_{cc}$ \cite{4}.}
According Fig. 1, one can obtain

\[
\begin{align*}
\mathcal{M}_1 &= -\kappa \bar{u}(p_{12})(-i\gamma^\nu)(v(p_2)\bar{u}(p_{11})(-i\gamma^\nu)(m_c + \bar{p}_1 + \bar{p}_2)\bar{\ell}(p_0)(c + \gamma^5)v(p_3),
\mathcal{M}_2 &= -\kappa \bar{u}(p_{12})(-i\gamma^\nu)(m_c + \bar{p}_1 + \bar{p}_3)\bar{\ell}(p_0)(c + \gamma^5)v(p_2)\bar{u}(p_{11})(-i\gamma^\nu)v(p_3),
\mathcal{M}_3 &= -\kappa \bar{u}(p_{12})\ell(p_0)(c + \gamma^5)(m_c - \bar{p}_1 - \bar{p}_2 - \bar{p}_3)(-i\gamma^\nu)v(p_2)\bar{u}(p_{11})(-i\gamma^\nu)v(p_3),
\mathcal{M}_4 &= -\kappa \bar{u}(p_{12})(-i\gamma^\nu)v(p_2)\bar{u}(p_{11})\ell(p_0)(c + \gamma^5)(m_c - \bar{p}_1 - \bar{p}_2 - \bar{p}_3)(-i\gamma^\nu)v(p_3),
\end{align*}
\]

where \( \kappa = -\frac{\alpha_s g^2}{4\cos\theta_w \sin\theta_w} \) with \( C \) denoting the color factor. \( c(p_0) \) is the polarization vector of the initial \( Z \) boson. The coefficient \( c \) reads

\[
c = \frac{8}{3} \sin^2 \theta_w - 1. \tag{4}
\]

The momenta of the constituent quarks in the diquark follow as

\[
p_{11} = \frac{m_c}{M_{cc}}p_1 + q \quad \text{and} \quad p_{12} = \frac{m_c}{M_{cc}}p_1 - q, \tag{5}
\]

where \( m_c = M_{cc}/2 \) is implicitly adopted to ensure the gauge invariance of the hard scattering amplitude; \( q(\approx 0) \) is the relative momentum between the two constituent \( c \) quarks inside the diquark.

By inserting the charge conjugate matrix \( C = -i\gamma^2\gamma^0 \) that satisfies the following equations [44],

\[
CC^{-1} = 1, \quad v^T(p)C = -\bar{u}(p), \quad C^{-1}u(p)^T = v(p),
\]

\[
C^-(\gamma^\mu)^T C = -\gamma^\mu, \quad C^-(\gamma^\mu\gamma^5)^T C = \gamma^\mu\gamma^5,
\]

\[
C^{-1}s_f^T(k, m)C = s_f(-k, m), \tag{6}
\]

the amplitudes in Eq. (3) can be rewritten as

\[
\begin{align*}
\mathcal{M}_1 &= -\kappa \bar{u}(p_{12})(-i\gamma^\nu)\Pi_{\mu\nu}^{[n]}(m_c + \bar{p}_1 + \bar{p}_2)\bar{\ell}(p_0)(c + \gamma^5)v(p_3),
\mathcal{M}_2 &= -\kappa \bar{u}(p_{12})(-i\gamma^\nu)(m_c - \bar{p}_1 - \bar{p}_3)\bar{\ell}(p_0)(c + \gamma^5)\Pi_{\mu\nu}^{[n]}(-i\gamma^\nu)v(p_3),
\mathcal{M}_3 &= -\kappa \bar{u}(p_{12})\ell(p_0)(c - \gamma^5)(m_c + \bar{p}_1 + \bar{p}_2 + \bar{p}_3)(-i\gamma^\nu)\Pi_{\mu\nu}^{[n]}(-i\gamma^\nu)v(p_3),
\mathcal{M}_4 &= -\kappa \bar{u}(p_{12})(-i\gamma^\nu)\Pi_{\mu\nu}^{[n]}(m_c - \bar{p}_1 - \bar{p}_2 - \bar{p}_3)(-i\gamma^\nu)v(p_3)
\end{align*}
\]

\[
(7)
\]
where $\Pi_q^{[\alpha]}$ denotes the spin projector operators \[65\],

$$
\Pi_q^{[1S_0]} = \frac{1}{\sqrt{8m_c^3}} \left( \frac{q}{2} - m_c \right) \gamma^5 \left( \frac{q}{2} + m_c \right),
$$

$$
\Pi_q^{[3S_1]} = \frac{1}{\sqrt{8m_c^3}} \left( \frac{q}{2} - m_c \right) \hat{q} \left( \frac{q}{2} + m_c \right). \tag{8}
$$

\section*{C. Color Factor}

According to Fig. 1, the color factor $C$ can be expressed as

$$
C = T_{im}^a T_{jn}^a, \tag{9}
$$

where $a = 1 \cdots 8$ is the color indices of the incoming gluon; $i, j = 1, 2, 3$ and $m, n = 1, 2, 3$ denote the color indices of the two constituent $c$ quarks in the diquark and that of the two final-state $\bar{c}$ quarks, respectively. By the fact that $3 \otimes 3 = \bar{3} \oplus 6$ in SU$_c$(3) group, the diquark can be either in anti-triplet $\bar{3}$ or in sextuplet 6 color state; in this case, we introduce the function $G_{ijk}^k_N$ to describe the diquark color, $k = 3$ and $N = \sqrt{2}$ being the color indices of the diquark and the normalized factor, respectively. $G_{ijk}$ is identical to the antisymmetric $\varepsilon_{ijk}$ (3) or the symmetric $f_{ijk}$ (6), which satisfies the following equations

$$
\varepsilon_{ijk} \varepsilon_{i'j'k} = \delta_{ii'} \delta_{jj'} - \delta_{ij} \delta_{i'j'},
$$

$$
f_{ijk} f_{i'j'k} = \delta_{ii'} \delta_{jj'} + \delta_{ij} \delta_{i'j'}. \tag{10}
$$

\section*{III. PHENOMENOLOGICAL RESULTS}

The input parameters in our calculations are set as

$$
m_Z = 91.1876 \text{ GeV}, \quad m_c = 1.8 \pm 0.05 \text{ GeV},
$$

$$
\sin^2 \theta_w = 0.23116, \quad \alpha = 1/137. \tag{11}
$$

According to the velocity scaling rule of NRQCD, we adopt the usual assumption that the matrix elements $h^{[3S_1]}_3$ and $h^{[1S_0]}_6$ have the equal values \[13, 28, 44\], which are given by the wave function at the origin \[22, 44\]

$$
h^{[3S_1]}_3 = h^{[1S_0]}_6 = |\Psi_{cc}(0)|^2 = 0.039 \text{ GeV}^3. \tag{12}
$$
| $\mu_r$ | $m_c$ (GeV) | $\Gamma[^3S_1]_{\bar{3}}$ | $\Gamma[^1S_0]_6$ | $\Gamma_{\text{Total}}$ | $B(\times 10^{-5})$ |
|-------|-----------|----------------|----------------|----------------|----------------|
| 1.75  | 16.36     | 58.87          | 75.23          | 3.015          |
| $2m_c$| 1.80      | 14.59          | 52.51          | 67.10          | 2.689          |
| 1.85  | 13.33     | 48.01          | 61.34          | 2.458          |
| $m_Z/2$| 1.80      | 4.79           | 17.21          | 22.00          | 0.882          |
| 1.85  | 4.05      | 14.57          | 18.62          | 0.746          |

We summarize the predicted decay widths of $Z \to \Xi_{cc} + X$ in Tab. I. Inspecting the data, one can find the branching ratio of $Z \to \Xi_{cc} + X$ amounts to $\sim 10^{-5}$, which is comparable with the color-singlet predictions of $B_{Z \to J/\psi + X}$ [66, 67]. In the predictions of the total decay width, the state of $(cc[^3S_1]_{\bar{3}}$ plays the leading role, more than three times bigger in magnitude than that of $(cc[^1S_0]_6$. Varying $m_c$ around the default value of 1.8 GeV by $\pm 0.05$ GeV would arouse a 10% variation of the decay width.

Based on the aforementioned capability of hunting $Z$ boson at LHC and CEPC, about $10^4$ (LHC) and $10^7$ (CEPC) $\Xi_{cc}$ production events arisen from $Z$ decay would be collected in one running year at the two colliders. By further considering the decay chains of $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ ($\sim 5\%$ [8]) or $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ ($\sim 10\%$ [11, 68]) with the cascade decay $\Lambda_c^+ \to pK^- \pi^+$ ($\sim 5\%$ [8]), we would accumulate about 10 and $10^4$ reconstructed $\Xi_{cc}^{+(++)}$ events at LHC and CEPC, respectively. Note that, the proposed HL(E)-LHC upgrade program may largely increase the $\Xi_{cc}$ yield events.

We are now in a position to estimate the ratio of the production rate of $\Xi_{cc}^{+(++)}$ in $Z$ decay to that of $\Lambda_c^+$. According to $B_{Z \to \Lambda_c^+} = B_{Z \to \Xi_{cc}^+} \times f_{c \to \Lambda_c} = 0.12 \times 0.057 = 6.84 \times 10^{-3}$, [61, 69] we have

$$R_{\Xi_{cc}^+} = \frac{\Gamma(Z \to \Xi_{cc}^+) \times B(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\Gamma(Z \to \Lambda_c^+)} = 0.85^{+0.10}_{-0.07} \times 10^{-4},$$

$$R_{\Xi_{cc}^{++}} = \frac{\Gamma(Z \to \Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\Gamma(Z \to \Lambda_c^+)} = 1.70^{+0.20}_{-0.14} \times 10^{-4},$$

where $\mu_r = 2m_c$ and the uncertainties are caused by $m_c = 1.8 \pm 0.05$ GeV. From the ratios one can perceive the predicted $R_{\Xi_{cc}^{+(++)}}$ in $Z$ decay is comparable with the measurements of LHCb (13 TeV) [9, 14] and Belle collaborations [15], while still significantly below the
Fig. 2: $\Xi_{cc}$ energy distributions in $Z \to \Xi_{cc} + X$ with $z$ defined as $\frac{2E_{\Xi_{cc}}}{m_Z}$.

SELEX-reported $R_{\Xi_{cc}^\pm}$.

At last, we give the predictions of the $\Xi_{cc}$ energy distributions in Fig. 2. The peak of $\frac{d\Gamma}{dz}|_{(cc)[^3S_1]_3}$ is around $z = 0.75$ and $\frac{d\Gamma}{dz}|_{(cc)[^1S_0]_6}$ peaks near $z = 0.7$. That the peak of $\Xi_{cc}$ energy distribution in $Z \to \Xi_{cc} + X$ lies in the large $z$ region can primarily be attributed to the dominance of the $c$-quark fragmentation mechanism.

IV. SUMMARY

In this manuscript, we apply the NRQCD factorization to study the $Z$ boson decaying into inclusive doubly-charmed baryon. By including the contributions of the di-quark states $(cc)[^3S_1]_3$ and $(cc)[^1S_0]_6$, the branching ratio of $B_{Z \to \Xi_{cc} + X}$ is predicted to be $\sim 10^{-5}$, following which as high as $10^4(7)$ $\Xi_{cc}$ events from $Z$ decay are expected to be accumulated at LHC (CEPC) per year. By comparing to the measurements on $B_{Z \to \Lambda_{cc}^{++} + X}$, we predict $R_{\Xi_{cc}^\pm}(= \frac{\Gamma(Z \to \Xi_{cc}^\pm) \times B(\Xi_{cc}^\pm \to \Lambda_{cc}^{++} K^- \pi^+)}{\Gamma(Z \to \Lambda_{cc}^0)} = (0.85 \pm 0.10) \times 10^{-4}$ and $R_{\Xi_{cc}^{++}}(= \frac{\Gamma(Z \to \Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \to \Lambda_{cc}^{++} K^- \pi^+ \pi^+)}{\Gamma(Z \to \Lambda_{cc}^0)} = (1.70 \pm 0.20) \times 10^{-4}$, where the uncertainties are estimated using alternative choices of the $c$-quark mass. Our prediction of $R_{\Xi_{cc}^{++}(++)}$ in the course of $Z$ decay is still inconsistent with the SELEX data but compatible with the LHCb- and Belle-measured values.

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