INCLUSIVE PRODUCTION OF FOUR CHARM HADRONS AT B-FACTORIES

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Measurements by the Belle Collaboration of the exclusive \( J/\psi + \eta_c \) and inclusive \( J/\psi + c\bar{c} + X \) productions in \( e^+e^- \) annihilation differ substantially from theoretical predictions based on the nonrelativistic QCD factorization approach. In order to test if such a discrepancy is originated from the large perturbative corrections to the hard-scattering amplitude, we study inclusive production of four charm hadrons in \( e^+e^- \) annihilation at B factories.

The nonrelativistic QCD (NRQCD) factorization formalism\(^1\) has enjoyed considerable success in describing production and decay rates of heavy quarkonia. The approach provides an infrared-safe prediction for the \( P \)-wave quarkonium decay\(^2\) and explains the large empirical cross sections of prompt charmonia at the Fermilab Tevatron.\(^3\) However, there are a few serious challenges to NRQCD. The first issue is the discrepancy between the NRQCD prediction and the CDF data for the polarization of prompt \( J/\psi \) in large-\( p_T \) bins.\(^4\) The measurement also confronts with a recent lattice NRQCD calculation, which supports the dominance of transverse \( J/\psi \).\(^5\),\(^6\) The second issue is for the \( J/\psi \) production in \( e^+e^- \) annihilation at \( B \)-factories. The cross sections for exclusive production of \( J/\psi + \eta_c \) in \( e^+e^- \) annihilation measured by the Belle Collaboration\(^7\),\(^8\) and by the Babar Collaboration\(^9\) are greater than NRQCD predictions of leading-order QCD\(^10\) by an order of magnitude. A few proposals\(^11\) introduced to solve the problem were disfavored by a recent experimental analysis.\(^8\) The next-to-leading-order QCD corrections to the exclusive process have been found to be as large as 80%\(^12\) of the leading-order prediction.\(^10\)

It is argued that nonperturbative corrections may be large.\(^13\) However, these corrections are not yet sufficient to explain the data. It would be interesting to see if such a large perturbative correction is also true in inclusive production of four charm hadrons\(^14\) having a similar parton-level process.

Another large discrepancy between the NRQCD prediction and the \( B \)-factory data is for the inclusive prompt \( J/\psi + c\bar{c} \) production cross section \( \sigma(e^+e^- \rightarrow J/\psi + c\bar{c} + X) \). Measured cross section\(^14\) is significantly larger than the NRQCD predictions.\(^15\),\(^16\)\(^17\) In order to find if an alternative way could re-
solve the problem, a process\cite{18} was recently studied within the color-evaporation model (CEM).\cite{19,20,21,22} The CEM prediction for the cross section \(\sigma(e^+e^- \rightarrow J/\psi + c\bar{c} + X)\) was reportedly smaller than the empirical value by about two orders of magnitude.\cite{18} A more comprehensive discussion of the CEM can be found in Refs.\cite{23,24,25}. The Belle Collaboration also measured the fraction \(R[J/\psi + c\bar{c}]\) of the process within inclusive \(J/\psi\) production. The measured value, \(R[J/\psi + c\bar{c}]_{\text{Belle}} = 0.82 \pm 0.15 \pm 0.14\)\cite{17,20} is significantly larger than the NRQCD predictions of about 15%. In the CEM, there is only a single universal nonperturbative factor, which perfectly cancels in the ratio \(R[J/\psi + c\bar{c}]\). Thus, the CEM prediction for the ratio is expected to be more reliable than the absolute values for the cross sections in the numerator and the denominator. Here we briefly review the production of four charm hadrons in \(e^+e^-\) annihilation at \(B\) factories.

Since the inclusive four charm hadron production involves the same Feynman diagrams for exclusive \(J/\psi + \eta_c\) production, measuring the cross section will provide an important information in the estimating the size of the short-distance coefficient for \(J/\psi + \eta_c\) cross section. We present \(\sigma(e^+e^- \rightarrow c\bar{c} + X)\) prediction in leading order of strong coupling constant, \(\alpha_s^2\).

Our predictions for the inclusive four charm hadron cross sections in \(e^+e^-\) annihilation at \(\sqrt{s} = 10.6\) GeV depending on the charm quark mass \(m_c\) is shown in Fig. 1(a). The cross section for \(e^+e^- \rightarrow c\bar{c} + X\) is very sensitive to the value of \(m_c\). For \(\alpha = 1/137, \alpha_s = 0.2, m_c = 1.5\) GeV \(\sigma(e^+e^- \rightarrow c\bar{c}) = 97\) fb. The cross section

Fig. 1. (a) Total cross section \(\sigma(e^+e^- \rightarrow c\bar{c})\) at \(\sqrt{s} = 10.6\) GeV in pb as a function of \(m_c\), where \(\alpha = 1/137\) and \(\alpha_s = 0.2\). (b) Differential cross section \(d\sigma/dm_{cc}\) in fb/GeV with respect to the invariant mass \(m_{cc}\) of \(cc\) for \(e^+e^-\) annihilation into \(c\bar{c} + X\), where \(\alpha = 1/137, \alpha_s = 0.2\). Physical range of the \(m_{cc}\) is from 2\(m_c\) to \(\sqrt{s} - 2m_c\). The area under the curves are the integrated cross sections 97 fb. From Ref. 14.
varies from 0.31 pb at \( m_c = 1.2 \text{ GeV} \) to 24 fb at \( m_c = 1.8 \text{ GeV} \). The cross section decreases as \( m_c \) increases mainly because available phase space shrinks. If one can increase the c.m. energy of the \( e^+e^- \), the \( m_c \) dependence will decrease.

In Fig. 1(b) we show the differential cross section with respect to the invariant mass of \( cc \). This is the prediction for \( d\sigma(e^+e^- \to cc + X)/dm_{cc} \) in leading order in \( \alpha_s \). Experimentally, this differential cross section can be compared with the \( \sum_{H,H'} d\sigma(e^+e^- \to HH' + X)/dm_{HH'} \), where \( H \) and \( H' \) are charm hadrons, which do not include anticharm.

With \( \sigma(e^+e^- \to cc + X) \approx 0.1 \text{ pb} \) and current integrated luminosity \( \mathcal{L} \approx 300 \text{ fb}^{-1} \) we expect roughly 30 events will be detected by the Belle detector. If our leading-order prediction is comparable to the measured value, it is very probable that the QCD higher-order corrections to the \( J/\psi + \eta_c \) cross section is small. Then the large discrepancy in \( J/\psi + \eta_c \) cross section may be due to the violation of factorization or existence of new production mechanism. If the measured cross section for the four charm hadron inclusive production is much larger than our prediction like the case of \( J/\psi + \eta_c \), it is very likely that perturbative QCD corrections to \( J/\psi + \eta_c \) cross section is large enough to explain the discrepancy, which leads to the failure of reliability in perturbative expansion.

Acknowledgments

We thank Taewon Kim, Pyungwon Ko, and Jong-Wan Lee for their collaboration on parts of the work presented here. This work was supported by the Basic Research Program of the Korea Science and Engineering Foundation (KOSEF) under grant No. R01-2005-000-10089-0 and by the SK Group under a grant for physics research at Korea University.

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