PROCEEDINGS OF SCIENCE

Double quarkonium production at the LHC

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Within the framework of nonrelativistic QCD factorization (NRQCD) approach, we investigate inclusive productions of two spin-triplet S-wave quarkonia at the Large Hadron Collider. The total cross sections for $pp \to 2J/\psi + X$, $pp \to 2\Upsilon + X$, and $pp \to J/\psi + \Upsilon + X$ integrated over the rapidity range $|y| \leq 2.4$ are 35 nb, 49 pb, and 13 pb at the center-of-momentum energy $\sqrt{s} = 14$ TeV, respectively. We find that the color-singlet channels dominate over the color-octet channels in the $pp \to 2J/\psi + X$ and $pp \to 2\Upsilon + X$ processes, while the color-octet channels may be enhanced at large transverse momentum. We find that in the $pp \to J/\psi + \Upsilon + X$ process, the color-singlet channel is much suppressed compared to the color-octet channel at leading order in the strong coupling α_s, especially, at large transverse momentum. Therefore, the $pp \to J/\psi + \Upsilon + X$ process may provide a good probe to the color-octet mechanism or give a stringent bound on the color-octet matrix elements.

35th International Conference of High Energy Physics - ICHEP2010,
July 22-28, 2010
Paris France

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[†]This work was supported by Basic Science Research Program through the NRF of Korea funded by the MEST under Contract 2009-0072689.

PoS(ICHEP 2010)220

1. Introduction

Heavy quarkonium production and decay have provided a probe of both perturbative and nonperturbative aspects of QCD. As an effective theory of QCD, nonrelativistic QCD (NRQCD) [1] is a theoretical tool to describe the production of heavy quarkonium. It has achieved great successes in resolving the infrared divergence problem in the decay of a P-wave quarkonium [2]. The double-quarkonium production at the B factories are well understood by taking into account both the next-to-leading-order corrections in the strong coupling α_s and relativistic corrections in the heavy-quark velocity v in the heavy-quarkonium rest frame [3, 4, 5].

However, there are still unresolved problems. One of them is the polarization of prompt J/ψ at the Tevatron, which are predicted to be transverse at large transverse momentum (p_T) from the color-octet dominance of NRQCD [6]. This prediction is inconsistent with empirical data at CDF, where the J/ψ is almost unpolarized even at high p_T [7]. The prediction strongly depends on the determination of the NRQCD matrix elements responsible for the hadronization of the heavy-quark-antiquark pair. The nonobservation of strongly transverse polarization of prompt J/ψ indicates that the color-octet matrix element $\langle O_8^{J/\psi}(^3S_1)\rangle$ might have been overestimated. Furthermore, the color-octet matrix elements from various processes are not consistent with each other [8, 9, 10].

In this respect, it is desirable to propose the processes to probe the color-octet mechanism of NRQCD and constrain the NRQCD matrix elements. In this work, we show that the inclusive spin-triplet S-wave double-quarkonium production at the LHC may be a promising candidate to test NRQCD and to probe the color-octet mechanism clearly. For the details of the method to calculate the cross section and the input parameters, we refer the readers to Ref. [11, 12].

2. $pp \to 2J/\psi(2\Upsilon) + X$ at the LHC

In this section, we consider the inclusive identical spin-triplet S-wave quarkonium pair production $pp \to 2H + X$ at the LHC, where H is J/ψ or Υ. As a parton-level process contributing to the process, we take into account only the gg initial states, which is dominant at the energy scale of the LHC. In this case, the color-singlet channel $Q\bar{Q}_1(^3S_1) + Q\bar{Q}_1(^3S_1)$, where $Q = c$ or b, is dominant over the color-octet channels unless there is any enhancement factor for other states to compensate the power suppression compared to the color-singlet channel. The color-octet channel $Q\bar{Q}_8(^3S_1) + Q\bar{Q}_8(^3S_1)$ is suppressed by a relative order v_Q^8 compared to the color-singlet channel, but the suppression factor may be overcome at large p_T due to the double-gluon-fragmentation dominance. Except for this color-octet channel, the other color-octet channels do not have any large enhancement factor to compete with either $Q\bar{Q}_1(^3S_1)$ or $Q\bar{Q}_8(^3S_1)$ contribution.

We show the p_T distribution for the $pp \to 2J/\psi + X$ and $pp \to 2\Upsilon + X$ processes integrated over the rapidity range $|y| < 2.4$ at the center-of-momentum energy $\sqrt{s} = 14$ TeV in Fig. 1 (a) and (b), respectively. The dashed, dotted, and solid lines represent the color-singlet $[Q\bar{Q}_1(^3S_1) + Q\bar{Q}_1(^3S_1)]$ contribution, color-octet $[Q\bar{Q}_8(^3S_1) + Q\bar{Q}_8(^3S_1)]$ contribution, and the sum of the two contributions, respectively. As shown in Fig. 1, the color-singlet channel dominates in the small p_T region while the color-octet channel dominates over the color-singlet channel at large p_T. The crossovers are placed at $p_T \approx 16$ GeV and 24 GeV for $pp \to 2J/\psi + X$ and $pp \to 2\Upsilon + X$, respectively. The integrated cross sections are 35 nb and 49 pb for $pp \to 2J/\psi + X$ and $pp \to 2\Upsilon + X$

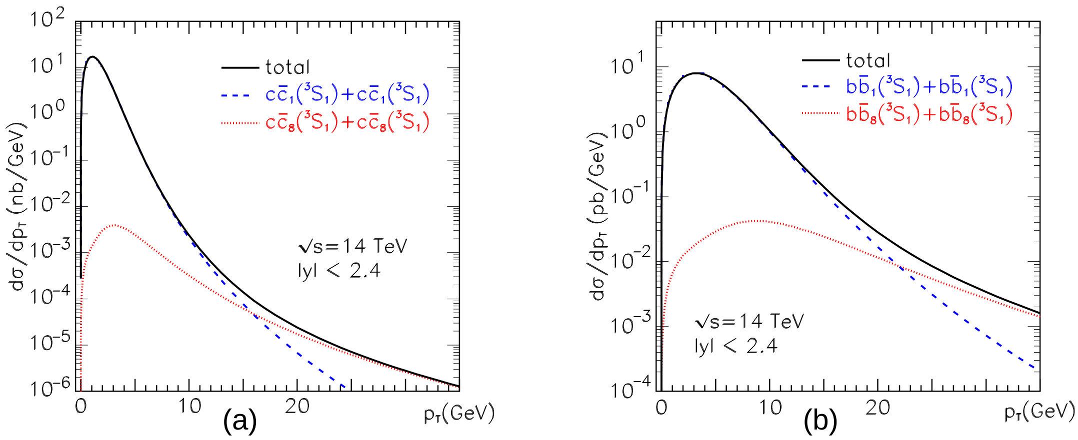

Figure 1: The differential cross sections for (a) $pp \to 2J/\psi + X$ and (b) $pp \to 2\Upsilon + X$ at $\sqrt{s} = 14$ TeV in units of nb/GeV and pb/GeV as functions of p_T integrated over the rapidity range $|y| < 2.4$.

at $\sqrt{s} = 14$ TeV, respectively. We emphasize that in order to probe the color-octet mechanism in the inclusive identical spin-triplet S-wave quarkonium pair production one must measure the events with extremely high p_T.

3. $pp \to J/\psi + \Upsilon + X$ at the LHC

In this section, we consider the $pp \to J/\psi + \Upsilon + X$ process. As in the double-quarkonium production of the same flavor, the gg fusion process is dominant at the LHC. First we consider the color-octet channel $gg \to c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$, whose velocity-scaling factor is $v_c^4 v_b^4$. In spite of the suppression factor, this parton-process may dominates the cross section at large p_T because of the large kinematic enhancement arising from the double-gluon fragmentation diagrams. The mixed contributions $c\bar{c}_1(^3S_1) + b\bar{b}_8(^3S_1)$ and $c\bar{c}_8(^3S_1) + b\bar{b}_1(^3S_1)$ are enhanced by $1/v_b^4$ or $1/v_c^4$ compared to the $c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$ channel. Thus the mixed contributions dominates over the color-octet channel $c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$ if p_T is not large. The other color-octet channels do not have any enhancement factors compared to the above three color-octet channels so we ignore them in this work.

The leading-order color-singlet contribution to $pp \to J/\psi + \Upsilon + X$ is suppressed compared to the color-octet contribution by α_s^2. The corresponding parton-level diagrams should radiate two real gluons except for the J/ψ and Υ in the final state or have the two gluon exchanges between the $c\bar{c}$ and $b\bar{b}$ lines which eventually evolve into the J/ψ and Υ, respectively. We note that the color-singlet contributions have the enhancement factor $1/(v_c^4 v_b^4)$ compared to the color-octet contribution $c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$ from the velocity-scaling rules of NRQCD. However, if one considers the large kinematic factor for the color-octet contribution at large p_T arising from the double-gluon fragmentation, the suppression factor for the color-singlet contribution relative to the color-octet contribution is $[\alpha_s/(4\pi)]^2 [m_c/(v_c p_T)]^4 [m_b/(v_b p_T)]^4$. This factor indicates that the color-singlet contribution is well suppressed compared to the color-octet contribution at large p_T.

If p_T is small, the suppression factors for the color-singlet contribution to the mixed contributions $c\bar{c}_1(^3S_1)+b\bar{b}_8(^3S_1)$ and $c\bar{c}_8(^3S_1)+b\bar{b}_1(^3S_1)$ are estimated to be $\sim \alpha_s/[(4\pi)^2 v_b^4]$ or $\sim \alpha_s/[(4\pi)^2 v_c^4]$, which are much less than order 1. Hence we conclude that the color-singlet contribution is well suppressed compared to the color-octet contribution in both the large and small p_T regions.

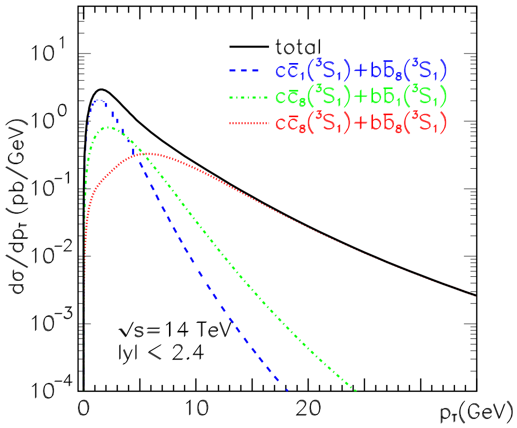

Figure 2: The differential cross sections for $pp \to J/\psi + \Upsilon + X$ at $\sqrt{s} = 14\,\text{TeV}$ in units of pb/GeV as a function of p_T integrated over the rapidity range $|y| < 2.4$.

We show the p_T distribution for the $pp \to J/\psi + \Upsilon + X$ process integrated over the rapidity range $|y| < 2.4$ at $\sqrt{s} = 14$ TeV in Fig. 2. The dashed, dashed-dotted, dotted, and solid lines represent the $[c\bar{c}_1(^3S_1) + b\bar{b}_8(^3S_1)]$ contribution, $[c\bar{c}_8(^3S_1) + b\bar{b}_1(^3S_1)]$ contribution, $[c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)]$ contribution, and the sum of the three contributions, respectively. The $[c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)]$ contribution dominates at $p_T > 6$ GeV while the $[c\bar{c}_1(^3S_1) + b\bar{b}_8(^3S_1)]$ contribution dominates at $p_T < 4$ GeV. In the intermediate region 4 GeV $< p_T <$ 6 GeV, these three contributions compete among one another. The cross section integrated over $|y| < 2.4$ is 13 pb at $\sqrt{s} = 14$ TeV. Assuming the integrated luminosity $\sim$ 100 fb^{-1}, we expect about 1900 events for $pp \to J/\psi + \Upsilon + X$ followed by $J/\psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$. Therefore, we conclude that the p_T distribution of $pp \to J/\psi + \Upsilon + X$ will be measured at the LHC so this process may be a clean probe to the color-octet mechanism. If the forthcoming measured cross section is significantly less than our prediction, it may indicate that the current values for the color-octet matrix elements are overestimated.

4. Discussions

We obtained the p_T distribution for $pp \to 2J/\psi + X$, $pp \to 2\Upsilon + X$, and $pp \to J/\psi + \Upsilon + X$ at $\sqrt{s} = 14$ TeV. The total cross sections integrated over $|y| < 2.4$ are 35 nb, 49 pb, and 13 pb, respectively. For the double-quarkonium production of the same flavor, the color-singlet contribution is dominant at small p_T while the color-octet contribution is dominant at large p_T. The crossovers are placed at $p_T \approx 16$ GeV for $pp \to 2J/\psi + X$ and 24 GeV for $pp \to 2\Upsilon + X$, respectively. Thus in order to probe the color-octet mechanism in the double-quarkonium production of the same flavor, one must collect events with extremely high p_T. If we apply the cuts $p_T \gtrsim 16$ and 24 GeV for the $2J/\psi$ and 2Υ final states in order to reduce the color-singlet background, the resultant cross sections are about 0.2 pb and 0.05 pb, respectively. This implies that it may be difficult to probe the color-octet mechanism in the double-quarkonium production of the same flavor. In the case of $pp \to J/\psi + \Upsilon + X$, we do not need such a cut because the color-octet contributions dominate over the color-singlet contributions over the whole range of p_T. Therefore we conclude that the $pp \to J/\psi + \Upsilon + X$ process is the most sensitive to the color-octet mechanism. If one cannot observe the events at the desired level, it implies that the current values of the color-octet matrix elements are overestimated. We anticipate that our prediction can be tested at the LHC.

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