Associated production of $\Upsilon(1S)W$ at LHC in next-to-leading order QCD

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Abstract: We investigate the complete next-to-leading order (NLO) QCD corrections to $\Upsilon(1S) + W$ production at the LHC, and predict theoretically the distribution of the $\Upsilon(1S)$ transverse momentum. We analyse the contributions from different components up to the QCD NLO in the $pp \rightarrow \Upsilon(1S) + W + X$ process. Our results show that the $pp \rightarrow \Upsilon(1S) + W + X$ process has a large production rate and could be potentially detected at the LHC. We see that the differential cross section for the $\Upsilon(1S)$ direct-production at the LO is significantly enhanced by the QCD corrections, and the $\bar{b}\bar{b}[3S_1(8)]$ contribution component dominates in the whole plotted $p_T^{\Upsilon(1S)}$ region. We have also calculated the $\Upsilon(1S)$ meson indirect-productions via feed-down decays of $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\chi_{b1}(2P)$, and $\chi_{b2}(2P)$ mesons. We find that the $\Upsilon(1S)$ indirect-productions can give important contributions to the distribution of $p_T^{\Upsilon(1S)}$ for the $pp \rightarrow \Upsilon(1S) + W + X$ process at the NLO. We conclude that the studying the $\Upsilon(1S) + W$ production at the LHC could provide an interesting opportunity in testing the nonrelativistic QCD factorization formalism.

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1. Introduction

The study of heavy quarkonium is one of the interesting subjects in both theoretical and experimental physics, which offers a good testing ground for investigating the Quantum Chromodynamics (QCD) in both the perturbative and non-perturbative regimes. The factorization formalism of nonrelativistic QCD (NRQCD) [1] provides a rigorous theoretical framework to describe the heavy-quarkonium production and decay by separating the amplitude into two parts: a short-distance part which can be expanded as a sum of terms in the power of $\alpha_s$ and calculated perturbatively, and long-distance matrix elements (LDMEs), which can be extracted from experiment. The relative importance of the LDMEs can be estimated by means of velocity scaling rules [2]. A crucial feature of the NRQCD is that the complete structure of the quarkonium Fock space has been explicitly considered.

By introducing the color-octet mechanism (COM), NRQCD has successfully absorbed the infrared divergences into P-wave [1,3–6] and D-wave [7,8] decay widths of heavy quarkonium, which cannot be handled in the color-singlet mechanism (CSM). The COM can successfully reconcile the orders of magnitude discrepancies between the experimental data of $J/\psi$ production at the Tevatron [9] and the CSM theoretical predictions, even if it has been calculated up to the next-to-leading-order (NLO). Substantial progress has been achieved in the calculation of high order QCD corrections to charmonium production in order to clarify the validity and limitation of the NRQCD formulation. Recently, the complete NLO calculation for polarization and unpolarization of direct hadroproduction in NRQCD are presented by two groups [10–13]. For unpolarization of direct $J/\psi$ production in Ref. [11], two new linear combinations of color-octet matrix elements are obtained from the CDF data by the authors, and used to predict $J/\psi$ production at the LHC, which agree with the CMS data. $J/\psi$ polarization puzzle also may be understood as the transverse components canceling between $^3S_1^{(8)}$ and $^3P_J^{(8)}$ channels [10]. The other group performed a multi-process fit of the color-octet LDMEs for unpolarization of direct hadroproduction [12], and gave more global fitting results which are consistent with NRQCD scaling rules. While, they find that the CDF polarization data (Run-II) [14] can not be interpreted by using these fit
values [13]. Therefore, the existence of the COM is still under doubt and far from being proven.

The heavy quarkonium production associated with a gauge boson may be a good process in testing the COM. In high energy collider experiments, $W$, $Z$ and heavy quarkonium can be selected with purely leptonic decay modes [15], which are particularly useful in hadron collides, because they provide an enormous suppression of the background. The $W$ or $Z$ production associated with a $J/\psi$ has been studied [16]. In reference [16] the authors gave a theoretical prediction for associated production of heavy quarkonium and electroweak bosons at hadron collider at the LO, and the numerical results show that the transverse momentum distribution of heavy quarkonium production is smaller in the CSM than that in the COM at the LO. Recently, the NLO QCD corrections to $J/\psi + W$ and $J/\psi + Z$ associated productions at the LHC were calculated in nonrelativistic QCD [17, 18]. The numerical results show that the differential cross section at the LO is significantly enhanced by the NLO QCD corrections.

Since the mass of bottomonium is about 3 times of that of charmonium, the value of $v^2$ is smaller in bottomonium ($\approx 0.1$) than that in charmonium ($\approx 0.3$), the expansion in $v^2$ should converge faster in bottomonium. Therefore, the study of bottomonium may be a more suitable choice to test the NRQCD factorization formalism. The $\Upsilon(1S)$ production associated with a $W$- or a $Z$-boson at hadron colliders has been studied in Ref. [15]. It was found that the cross sections for $\Upsilon(1S) + W$ and $\Upsilon(1S) + Z$ productions are roughly 0.45 pb and 0.15 pb at the Tevatron and roughly 4 pb and 2 pb at the LHC respectively, and the dominant production mechanism is via the P-wave bottomonium production, which is a $b\bar{b}$ bound state of color-octet, and the bottomonium subsequently decays to $\Upsilon(1S)$. In experimental aspect, this process has been studied once at the Tevatron [19], but due to the limited sensitivity of the CDF experiment in Run I, they didn’t observe $\Upsilon(1S)$ mesons production in association with $W$- or $Z$-bosons at the Tevatron. Since the LHC has larger integrated luminosity and higher energy, we expect LHC experiments can achieve the sensitivity sufficient to observe the $\Upsilon(1S)$ plus a vector boson production. As we know, the NLO QCD corrections to quarkonium production are normally important in precision measurement [10–13]. It is necessary to provide a complete NLO theoretical prediction for $\Upsilon(1S)$ mesons in association with $W$- or $Z$-boson production, and compare the results with experiment.

In this paper we calculate the full NLO QCD corrections to the $\Upsilon(1S)$ production in association with a $W$-boson at the LHC. For this process, only the $^3S_1$ color-octet (the $b\bar{b}$ $^3S_1^{(8)}$ Fock state) provides contribution at the leading-order (LO). Even including the NLO QCD contributions up to $\alpha_s^3$ and $v^7$ of LDMEs, there are only color-octets $b\bar{b}$ $^1S_0^{(8)}$, $c\bar{b}$ $^3S_1^{(8)}$ and $b\bar{b}$ $^3P_J^{(8)}$ ($J = 0, 1, 2$), but no color-singlet contribute to the direct prompt $\Upsilon(1S)$ production in association with a $W$ gauge boson process. Therefore, the $\Upsilon(1S) + W$ production at the LHC can provide an ideal ground to study the COM. Meanwhile, The production of $\Upsilon(1S) + W$ may also provide lampposts for looking for new physics [15]. In the context of supersymmetric models (SUSY), a charged Higgs boson lighter than about 180 GeV have a sizable decay branching ratio into $\Upsilon(1S)W$ pairs if the ratio of vacuum
expectation values $\tan(\beta)$ is small. Therefore, the $\Upsilon(1S) + W$ production may be a very important background process for searching for charged Higgs boson in SUSY models.

The paper is organized as follows. We present the details of the calculation for the process $pp \rightarrow \Upsilon(1S) + W + X$ in Section 2. In Section 3, we give the numerical results and discussions at the LHC. Finally, a short summary is given.

2. Calculation descriptions

The strategy of the NLO QCD calculations in this work is similar to that used in the evaluations for the $pp \rightarrow J/\psi + W/Z$ process [17, 18]. For simplicity, we sketch it in this section.

The cross section for the $pp \rightarrow H + W$ process is expressed as

$$\sigma(pp \rightarrow H + W + X) = \int dx_1 dx_2 \sum_{i,j,n} \frac{\langle O^H[n] \rangle}{N_{\text{col}}(n) N_{\text{pol}}(n)} \hat{\sigma}(i+j \rightarrow b\bar{b}[n] + W + X) \times \left[G_{i/A}(x_1, \mu_f)G_{j/B}(x_2, \mu_f) + (A \leftrightarrow B)\right],$$

where $N_{\text{col}}(n)$ and $N_{\text{pol}}(n)$ refer to the numbers of colors and polarization $b\bar{b}(n)$ states produced [6], respectively. $\hat{\sigma}(i+j \rightarrow b\bar{b}[n] + W + X)$ is the cross section for the short distance production of a $b\bar{b}$ quark pair in the color, spin and angular momentum state $n$ at the parton level. $\langle O^H[n] \rangle$ is the long distance matrix element, which describes the hadronization of the $b\bar{b}$ quark pair into the observable bottomonium state $H$. $G_{i/A,B}$ are the parton distribution functions (PDFs), $A$ and $B$ refer to incoming protons at the LHC. $i,j$ represents gluon and all possible light quarks and anti-quarks ($i,j = u,d,s,c,\bar{u},\bar{d},\bar{s},\bar{c}$).

We ignore the processes which are suppressed by a tiny Kobayashi-Maskawa factor.

The short distance cross section for the production of a $b\bar{b}$ pair in a Fock state $n$, $\hat{\sigma}(i+j \rightarrow b\bar{b}[n] + W + X)$, is calculated from the amplitudes which are obtained by applying certain projectors onto the usual QCD amplitudes for open $b\bar{b}$ production. In the notations of Ref. [6] they are written as

$$A_{b\bar{b}[1S_0^{(1/8)}]} = \text{Tr}[C_{1/8}\Pi_0 A]_{q=0},$$

$$A_{b\bar{b}[3S_1^{(1/8)}]} = \epsilon_\alpha \text{Tr}[C_{1/8}\Pi_1^\alpha A]_{q=0},$$

$$A_{b\bar{b}[1P_1^{(1/8)}]} = \epsilon_\alpha \frac{d}{dq_\alpha} \text{Tr}[C_{1/8}\Pi_0 A]_{q=0},$$

$$A_{b\bar{b}[3P_1^{(1/8)}]} = \epsilon^{(J)}_{\alpha\beta} \frac{d}{dq_\beta} \text{Tr}[C_{(1/8)}\Pi_1^\alpha A]_{q=0},$$

where $A$ denotes the QCD amplitude with amputated bottom spinors, the lower index $q$ represents the momentum of the bottom quark in the $b\bar{b}$ rest frame. $\Pi_{0/1}$ are spin projectors.

(2.2)
onto the spin singlet and spin triplet states. $C_{1/8}$ are color projectors onto the color singlet and color octet states. $E_\alpha$ and $E_{\alpha\beta}$ represent the polarization vector and tensor of the $Q\bar{Q}$ states, respectively.

In the calculation for the LO of $\alpha_s$, only the Fock state $^3S_1^{(8)}$ is involved. However, in considering the NLO QCD corrections to $pp \to \Upsilon(1S) + W + X$ process, we should not only consider the contribution from virtual corrections, but also the contribution from real gluon/light-quark emission processes. We draw some representative Feynman diagrams for the process $pp \to \Upsilon(1S) + W + X$ at the LO and up to QCD NLO in Fig.1. The virtual corrections only occur in connection with the $b\bar{b}$ Fock state $^3S_1^{(8)}$, but the real gluon/light-quark emission process should involve $^1S_0^{(8)}, \ 3^3S_1^{(8)}$ and $3^3P_0^{(8)}$ Fock state contributions. In our calculations, we adopt the dimensional regularization (DR) method in $D = 4 - 2\epsilon$ dimensions to isolate the ultraviolet (UV), soft infrared (IR), and collinear IR singularities. There exist UV, soft, collinear and coulomb singularities in virtual corrections. In order to remove the UV divergences, we employ the modified minimal subtraction (MS) scheme to renormalize and eliminate UV divergency. After applying the renormalization procedure the UV divergences in the virtual correction part are canceled. The other appeared singularities can also be analytically canceled when we added all the NLO QCD contribution components together. In Fig.2, we present the IR and Coulomb singularity structures and divergence cancelation routes in the NLO QCD calculation for the $pp \to \Upsilon(1S) + W + X$ process.

The real gluon process with $^1S_0^{(8)}$ Fock state is free of divergence, while the contribution
from the real gluon process with $^3S_1^{(8)}$ Fock state has soft and collinear singularities, and the real gluon processes with $^3P_J^{(8)}$ Fock states has soft singularities. The soft divergences from the one-loop diagrams will be canceled by similar singularities from the $^3S_1^{(8)}$ state contribution of soft real gluon emission. As for the collinear divergences from the $^3S_1^{(8)}$ state contribution of soft real gluon emission corrections, part of it can be eliminated by collinear singularities in virtual corrections, and the remaining collinear divergences in real gluon corrections can be absorbed into the PDFs. Nevertheless, it still contains coulomb singularities in virtual corrections and soft singularities arising from the $^3P_J^{(8)}$ state contribution of real gluon process, these singularities is neither collinear nor infrared in the usual sense, and it can only be eliminated in the spirit of the factorization approach by taking the corresponding corrections to the operator $<\mathcal{O}^{I(1S)}[^3S_1^{(8)}]>$ into account. As for the light-quark emission process, there only involve initial state collinear divergences in $^3S_1^{(8)}$ state subprocess, and it also can be absorbed into the PDFs. Finally, after adding all contributions together, a result which is UV, soft, collinear, Coulomb finite is obtained.

We adopt the expressions in Ref. [20] to deal with the IR divergences in Feynman integral functions, and apply the expressions in Refs. [21–23] to implement the numerical evaluations for the IR safe parts of N-point integrals. In the virtual correction calculation, we find that only Fig.1(e) and Fig.1(f) induce coulomb singularities, and we use a small relative velocity $v$ between $b$ and $\bar{b}$ to regularize them [24]. The two cutoff phase space slicing method (TCPSS) [25] has been employed for dealing with the soft and collinear singularities in real gluon/light-quark emission corrections.

3. Numerical results and discussion

In the numerical calculations for the $pp \rightarrow \Upsilon(1S) + W + X$ process at the LHC, we
NLO when pp and NLO QCD corrected distributions of \( p_T \) production at the LHC (see Ref. [29]). The uncertainty varies from +8\% at the LO and from +18\% at the NLO QCD calculation, which determines from the CDF data [27,28]. In the calculation of real corrections, we adopt the two-cutoff phase space slicing method [25]. The two phase space cutoffs \( \delta_s \) and \( \delta_c \) are chosen as \( \delta_s = 10^{-3} \) and \( \delta_c = \delta_s / 50 \) as default choice. In checking the independence on two cutoffs \( \delta_s \) and \( \delta_c \), we find the invariance with the \( \delta_s \) running from \( 10^{-3} \) to \( 10^{-4} \) within the error control. Considering the validity of the NRQCD and perturbation method, we restrict our results to the domain \( p_T^{\Upsilon(1S)} > 3 \) GeV and \( |y_{\Upsilon(1S)}| < 3 \).

The dependence of the cross section on the renormalization scale \( \mu_r \) and factorization scale \( \mu_f \) induces uncertainty for theoretical prediction. In Fig. 3, the \( \mu \) dependence of the LO and the NLO QCD corrected cross sections with the constraints of \( p_T^{\Upsilon(1S)} > 3 \) GeV and \( |y_{\Upsilon(1S)}| < 3 \) for \( pp \rightarrow \Upsilon(1S) + W + X \) process, is shown with our default choice \( \mu = \mu_r = \mu_f \) and the definition of \( \mu_0 = m_T \). There \( \mu \) varies from \( \mu_0 / 4 \) to \( 4 \mu_0 \). Not like the usual expectation, Fig. 3 shows that the NLO QCD correction can not improve the LO scale independence for the \( pp \rightarrow \Upsilon(1S) + W + X \) process at the LHC. The related theoretical uncertainty varies from +8.1% to -8.6% at the LO and from +18.5% to -13.8% at the NLO when \( \mu \) goes from \( \mu_0 / 2 \) to \( 2 \mu_0 \). Actually, this behavior is similar to that of the Wbb production at the LHC (see Ref. [29]).

| \( H \) | \(< O_H^\mathcal{H} >\) | \(< O_H[^3S_0^{(8)}]\) in GeV | \(< O_H[^1S_0^{(8)}]\) in GeV |
|---|---|---|
| \( \Upsilon(1S) \) | \( 15 \times 10^{-2} \) GeV | \( 2.0 \times 10^{-2} \) GeV |
| \( \Upsilon(2S) \) | \( 4.5 \times 10^{-2} \) GeV | \( 0.6 \times 10^{-2} \) GeV |
| \( \chi_0(1P) \) | \( 2.03 \) GeV | \( 4 \times 10^{-2} \) GeV |
| \( \chi_0(2P) \) | \( 2.57 \) GeV | \( 6.5 \times 10^{-2} \) GeV |

Table 1: NRQCD matrix elements for bottomonium production, where colour-octet matrix element \( < O_H[^1S_0^{(8)}] > = 2 < O_H[^3F_0^{(8)}] > /m_b^2 \) has been assumed for simplicity, and \( m_b = 4.75 \) GeV.

In our numerical calculations, we add all the contributions of \( pp \rightarrow \Upsilon(1S) + W^+ + X \) and \( pp \rightarrow \Upsilon(1S) + W^- + X \) together. In Figs. 3(a) and (b), we present the LO and the NLO QCD corrected distributions of \( p_T^{\Upsilon(1S)} \) and the corresponding K-factors for the direct \( \Upsilon(1S) + W \) production at the \( \sqrt{s} = 8 \) TeV and the \( \sqrt{s} = 14 \) TeV LHC, respectively. For comparison, we also depict the contributions from the \( \bar{b}b[^1S_0^{(8)}] \), \( \bar{b}b[^3S_0^{(8)}] \) and \( \bar{b}b[^3P_1^{(8)}] \) Fock states in these figures. From the figures we can see that the LO and the NLO corrected differential cross sections are sensitive to \( p_T \) of \( \Upsilon(1S) \), and the LO differential cross section is significantly enhanced by the NLO QCD corrections, and the \( \bar{b}b[^3S_0^{(8)}] \)
Figure 3: The dependence of the LO and the NLO QCD corrected cross sections for the process $pp \rightarrow \Upsilon(1S) + W + X$ on the factorization scale and renormalization scale ($\mu/\mu_0$) at the $\sqrt{S} = 14$ TeV LHC where we define $\mu = \mu_f = \mu_r$ and $\mu_0 = m_T$.

Figure 4: The LO and NLO QCD corrected distributions of $p_T^{\Upsilon(1S)}$ and the corresponding K-factor for the direct $\Upsilon(1S) + W$ production. (a) at the $\sqrt{S} = 8$ TeV LHC. (b) at the $\sqrt{S} = 14$ TeV LHC.

collection contribution dominates in the whole plotted $p_T^{\Upsilon(1S)}$ region. In Fig.4(a), the NLO QCD corrected differential cross section of $p_T^{\Upsilon(1S)}$ at the $\sqrt{S} = 8$ TeV LHC decreases from 0.126 pb/GeV to 0.0026 pb/GeV as $p_T^{\Upsilon(1S)}$ increases from 3 to 50 GeV. In the range of $3 \text{ GeV} < p_T^{\Upsilon(1S)} < 50 \text{ GeV}$, the K-factor, defined as $K = \frac{d\sigma^{NLO}}{dp_T^{\Upsilon(1S)}}/\frac{d\sigma^{LO}}{dp_T^{\Upsilon(1S)}}$, varies in the range of [2.85, 4.96], and reaches its maximum when $p_T^{\Upsilon(1S)} = 3$ GeV. From Fig.4(b), we find that the NLO corrected differential cross section at the $\sqrt{S} = 14$ TeV LHC in the whole plotted $p_T^{\Upsilon(1S)}$ region can be quantitatively beyond 3 times of the corresponding LO differential cross section, and reaches its maximum $K = 5.33$ when $p_T^{\Upsilon(1S)} = 3$ GeV. We can read out from the figure that the NLO QCD corrected differential cross section varies
in the range of [0.211, 0.0053] pb/GeV when $p_T^{Y(1S)}$ runs from 3 GeV to 50 GeV, it reaches the maximum at the location of $p_T^{Y(1S)} = 4$ GeV.

We have investigated the direct production of $Y(1S)$ meson up to QCD NLO. The $Y(1S)$ meson can also be produced indirectly via radiative or hadronic decays of heavier bottomonium, such as $Y(2S)$, $Y(3S)$, $\chi_b(1P)$, $\chi_b(2P)$, $\chi_b(2P)$, and $\chi_b(2P)$ mesons. We know that these contributions are very important in studying $Y(1S)$ meson production [15]. To calculate these feed-down contributions for $Y(1S)$ meson production, the main problem is to determine the relation between momentum of higher excited states and momentum of $Y(1S)$. Following the method used in Ref. [30], we ignored the momentum shift when these excited states decay into $Y(1S)$. The cross sections of these six feed-down production channels can be obtained approximately by multiplying the direct-production cross section of the intermediate bottomonium production with its decay branching fraction to $Y(1S)$ meson. In our calculation, we ignored the contributions aroused from $\chi_b(1P,2P)$ feed-down into $Y(1S)$ for the smallness of the transition branching ratios.

The direct-production cross sections of the $Y(2S)$ and $Y(3S)$ can be calculated by using analogous method to the $Y(1S)$ production, and the relevant color-octet matrix elements of $Y(2S)$ and $Y(3S)$ used in our calculations are determined from the CDF data in Table 4 [27, 28]. In the calculation for the LO and the virtual corrections for the direct-production cross sections of the $\chi_b(1P)$, $\chi_b(2P)$, $\chi_b(2P)$ and $\chi_b(2P)$ mesons, only the Fock state $3S_1^{(8)}$ is involved. However, in considering the real gluon/light-quark emission corrections process, we should not only consider the contribution from $3S_1^{(8)}$ Fock state contribution, but also the contribution from $3P_J^{(1)}$ Fock state contributions. Based on NRQCD factorization formalism [6, 31], we can handle these calculations by adopting analogous method to the direct $Y(1S)$ production. For the NRQCD matrix elements of $\chi_{bJ}$, the color-singlet matrix elements are taken from the potential model calculation of Refs. [27, 32, 33], and the color-octet matrix elements are determined from the CDF data [27, 28]. The branching ratios of heavy bottomonium decays to $Y(1S)$ mesons used in this paper are taken form Ref. [34].

![Figure 5](image1.png)  

**Figure 5:** The complete NLO QCD corrected distributions of $p_T^{Y(1S)}$ for the $pp \rightarrow Y(1S) + W + X$ process. (a) at the $\sqrt{s} = 8$ TeV LHC. (b) at the $\sqrt{s} = 14$ TeV LHC.

The complete NLO QCD corrected distribution of $p_T^{Y(1S)}$ for the $pp \rightarrow Y(1S) + W + X$ process, the contributions of the $Y(1S)$ direct-production and the $Y(1S)$ indirect-
production by $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_b(1P)$, and $\chi_b(2P)$ mesons feed-down decays at the LHC are illustrated in Fig. 5. We can see that the $\Upsilon(1S)$ indirect-production can give important contribution to the distribution of $p_T^{\Upsilon(1S)}$ for the $pp \to \Upsilon(1S) + W + X$ process at the NLO. We find that when $p_T$ is smaller than about 7 GeV, the contribution from $\chi_b(1P)$ feed-down decays is about the same order of magnitude with the contributions of $\Upsilon(1S)$ direct-production when $\sqrt{s} = 8$ TeV, particularly at the $\sqrt{s} = 14$ TeV LHC the productions of $\chi_b(1P)$ feed-down decays provide the main contribution to $p_T^{\Upsilon(1S)}$ distribution for the $pp \to \Upsilon(1S) + W + X$ process. With the increment of the $p_T^{\Upsilon(1S)}$, the contributions of $\Upsilon(1S)$ indirect-production contributions decrease quickly, and the $\Upsilon(1S)$ direct-production contribution dominates at the large $p_T$ region.

4. Summary

In this paper we investigate the complete NLO QCD correction of $\Upsilon(1S) + W$ associated production at the LHC. This process is an ideal platform for studying color-octet mechanism. We adopt the dimensional regularization to deal with the UV and IR singularities in our calculation. The Coulomb and soft singularities in $P$ state are isolated and absorbed into the NRQCD NLO corrected operator $<O^{\Upsilon(1S)}[3S_1^{(8)}]>$. After adding all contribution components together, we get the results with UV, IR, Coulomb safety. We find that the production rate of the $pp \to \Upsilon(1S) + W + X$ process is quite large, and this process has the potential to be detected at the LHC. For the $\Upsilon(1S)$ direct-production, the differential cross sections at the LO are significantly enhanced by the QCD corrections, and the $b\bar{b}[3\bar{S}_1^{(8)}]$ contribution dominates in the range of $3 \text{ GeV} < p_T^{\Upsilon(1s)} < 50 \text{ GeV}$. In this paper, we also calculate the $\Upsilon(1S)$ meson indirect-production via radiative or hadronic decays of $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\chi_{b1}(2P)$, and $\chi_{b2}(2P)$ mesons. We find that the $\Upsilon(1S)$ indirect-production contributions can give important contribution to the distribution of $p_T^{\Upsilon(1S)}$ for the $pp \to \Upsilon(1S) + W + X$ process at the NLO. In the lower $p_T$ region, the contribution from indirect-production can give the main contribution to $p_T^{\Upsilon(1S)}$ in the $pp \to \Upsilon(1S) + W + X$ process. We conclude that if the $\Upsilon(1S) + W$ production is really detected at the LHC, it will be useful for testing the NRQCD factorization formalism.

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