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$\Upsilon(1S)$ prompt production at the Tevatron and LHC in nonrelativistic QCD

Kai Wang,[1] Yan-Qing Ma,[1] and Kuang-Ta Chao[1,2]

[1]*Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[2]*Center for High Energy Physics, Peking University, Beijing 100871, China*

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With nonrelativistic QCD factorization, we calculate the $\Upsilon(1S)$ prompt production at hadron colliders at next-to-leading order in α_s. In addition to the color-singlet contribution, color-octet channels (especially the P-wave channel) up to $O(v^4)$ are all considered. Aside from direct production, the feed-down contributions from higher excited S-wave and P-wave $b\bar{b}$ states to $\Upsilon(1S)$ production are also included. We use the potential model estimates as input for color-singlet long-distance matrix elements (LDMEs). While for color-octet contributions, we find they can be approximately described by three LDMEs: $\langle\mathcal{O}(^3S_1^{[8]})\rangle$, $\langle\mathcal{O}(^1S_0^{[8]})\rangle$ and $\langle\mathcal{O}(^3P_0^{[8]})\rangle$. By fitting the Tevatron data we can determine some linear combinations of these LDMEs, and then use them to predict $\Upsilon(1S)$ production at the LHC. Our predictions are consistent with the new experimental data of CMS and LHCb.

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I. INTRODUCTION

The study of heavy quarkonium production is particularly interesting because it may provide decisive information in understanding hadronization of heavy quarks and gluons in QCD. The most widely accepted theory to describe heavy quarkonium production at present is nonrelativistic QCD (NRQCD) factorization [1], in which the production is factorized into perturbative calculable short-distance coefficients and nonperturbative (and universal) long-distance matrix elements (LDMEs). As short-distance coefficients can be expanded in strong-coupling α_s and each LDME has a definite power in v (the velocity of heavy quarks in the rest frame of heavy quarkonium), NRQCD factorization gives predictions by double expansion in α_s and v^2. NRQCD factorization is efficient such that in principle only a finite number of universal parameters, which can be determined by using some known experimental data, are involved with required precision in predicting other production processes. Although a complete proof of factorization is still lacking, at least it holds up to next-to-next-to-leading order in α_s [2,3].

Based on NRQCD factorization, charmonium production in hadron colliders has been studied extensively in recent years [4–17]. Specifically, for J/ψ hadroproduction, it is found that all data at large p_T, including both yield and polarization, can be well described by NRQCD factorization if one chooses a large M_0 and a small M_1 [16] (see also Refs. [12,14]). Here M_0 and M_1 are linear combinations of related LDMEs which are defined in Refs. [12,14] and will also be mentioned below, and roughly speaking, their values represent the importance of p_T^{-6} behavior and p_T^{-4} behavior in J/ψ production cross sections, respectively.

There are reasons that studying bottomonium may be a more suitable choice than charmonium to test the NRQCD factorization formalism. First, the value of v^2 is smaller in bottomonium (≈ 0.1) than that in charmonium (≈ 0.3), thus the expansion in v^2 should converge faster in bottomonium. Second, the mass of bottomonium is about 3 times of that of charmonium, then asymptotic freedom implies the convergence of α_s expansion is also better in bottomonium. However, on the experiment side, the situation is not so satisfactory as the production rates of bottomonium are much smaller than charmonium, e.g., the cross section of $\Upsilon(1S)$ is about 2 orders of magnitude smaller than that of J/ψ. Furthermore, there are more excited bottomonium states which are below the open bottom (say $B\bar{B}$) threshold and can decay into lower bottomonium states such as $\Upsilon(1S)$ with large branching ratios and consequently contribute a substantial fraction to the lower bottomonium inclusive production by the so-called feed-down contributions, thus it is hard to measure the direct production from the prompt inclusive production. In the LHC era, we expect these disadvantages may be overcome by the higher luminosity, thus testing NRQCD factorization by bottomonium production seems to be hopeful.

The inclusive differential cross section and polarization of Υ are measured at the Tevatron [18–22], but the $\Upsilon(1S)$ polarizations observed by D0 [20] and CDF [21,22] disagree with each other. Furthermore, both the D0 and CDF measurements contradict the LO NRQCD prediction [23]. As argued in Refs. [11,14], the next-to-next-to-leading order and even higher-order contributions [24] may not be important, as compared with the full next-to-leading order (NLO) QCD contributions including both color-singlet (CS) and color-octet (CO) channels, which are essential in understanding the Υ

(and similarly the J/ψ) hadroproduction. Partial NLO QCD contributions to Υ hadroproduction have been calculated recently [4,7,9,25], and it is found that the NLO QCD corrections of S-wave CO channels only slightly change the transverse momentum distribution and the polarization, while the correction of CS channel may bring on significant enhancement to the momentum distribution and change the polarization from transverse at LO into longitudinal at NLO. But the NLO contributions of P-wave channels for Υ hadroproduction are still missing.

At the LHC, CMS has published the first run data for Υ production [26], and LHCb has also reported the measured result [27]. Thus it is timely to present a complete NLO theoretical prediction for Υ production, and compare theory with experiment. In this work, we study the $\Upsilon(1S)$ hadroproduction in the framework of NRQCD, including all NLO contributions and feed-down contributions. The paper is organized as follows. We briefly introduce our calculation in Sec. II. Then in Sec. III, we describe our method for taking into account the feed-down contributions. (Note that the feed-down contributions for $\Upsilon(1S)$ have not been treated seriously in all previous theoretical works.) In Sec. IV, we fit data to determine LDMEs and then give predictions for the LHC experiment. Finally, a summary is given in Sec. V.

II. NLO CALCULATION

The method of NLO calculation used in this work is similar to that used in J/ψ and χ_c production [11,12,14]. For completeness, we will sketch it in this section.

According to the NRQCD factorization formalism, the inclusive cross section for direct bottomonium H production in hadron-hadron collisions is expressed as

$$\begin{aligned} d\sigma[pp\to H+X] &= \sum_n d\hat{\sigma}[(b\bar{b})_n]\frac{\langle \mathcal{O}_n^H\rangle}{m_b^{2L_n}} \\ &= \sum_{i,j,n}\int dx_1 dx_2 G_{i/p}G_{j/p} \\ &\quad \times d\hat{\sigma}[i+j\to(b\bar{b})_n+X]\langle\mathcal{O}_n^H\rangle, \quad (1)\end{aligned}$$

where p is either a proton or an antiproton, the indices i, j run over all the partonic species, and n denote the color, spin and angular momentum (L_n) of the intermediate $b\bar{b}$ states. In this work, we calculate the cross sections up to v^4 corrections, so that the intermediate states include ${}^3S_1^{[1]}$, ${}^3P_J^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$. Note that our definition of CS LDMEs $\langle\mathcal{O}^H({}^3S_1^{[1]})\rangle$ and $\langle\mathcal{O}^H({}^3P_J^{[1]})\rangle$ are different from that in Ref. [1] by a factor of $1/(2N_c)$. The calculation proceeds with three steps: calculating the parton level differential cross section $d\hat{\sigma}[i+j\to(b\bar{b})_n+X]$, integrating over the phase space, and fitting the LDMEs.

NLO corrections for the parton level differential cross section include virtual corrections and real corrections. For virtual corrections, we use FEYNARTS [28] to generate Feynman diagrams and amplitudes. We then calculate these thousands Feynman diagrams analytically using our self-written MATHEMATICA code. Finally, we output the simplified expression into C++ code. Because the infrared divergence will appear when doing phase space integration for the real correction, we use the two cutoff phase space slicing method [29] to isolate the divergence. The contributions from the singular phase space part are calculated analytically, while finite parts are calculated by using the Berends-Giele off-shell recursive relations [30].

In the analytical calculation we have checked that all the ultraviolet (UV) and infrared (IR) singularities are canceled exactly. The UV divergences are removed by renormalization. The IR singularities arising from loop integration and phase space integration of the real correction partially cancel each other. The remaining IR singularities are absorbed into the proton parton-distribution functions and the NRQCD LDMEs.

The numerical integration over the phase space is handled by our self-written C++ codes, where we also use both QCDLOOP [31] and LOOPTOOLS [32] to calculate the scalar functions in the virtual corrections numerically. We verified that our results are independent of the two cuts introduced by the phase space slicing method. The method of fitting LDMEs will be discussed in Sec. IV.

III. TREATMENT OF FEED-DOWN CONTRIBUTION

One difficulty in predicting Υ production cross section is the treatment of feed-down contribution. There are several higher excited states that can decay into $\Upsilon(1S)$ and they include: $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$. Unfortunately, there are not enough data to determine LDMEs of these higher excited states, therefore, it is hard to predict their feed-down contributions to $\Upsilon(1S)$. In fact, all previous predictions that were based on NRQCD factorization did not have a serious treatment of the feed-down contributions.

The key point to deal with feed-down contribution is to determine the relation between momentum of higher excited states and momentum of $\Upsilon(1S)$. In Ref. [12], we find a very good approximation that the ratio of two momenta is inversely proportional to the ratio of their masses. Notice that the mass differences between these excited states and $\Upsilon(1S)$ are of the order of $m_b v^2$ and v^2 is very small in bottomonium, as a result, unlike the J/ψ case, the momentum shift can be ignored when these excited states decay into $\Upsilon(1S)$. Hence the production LDMEs can be approximately combined into 6 independent ones:

$$\begin{aligned}
\langle\mathcal{O}(^3S_1^{[1]})\rangle &= \langle\mathcal{O}^{\Upsilon(1S)}(^3S_1^{[1]})\rangle + \sum_{n=2,3}\langle\mathcal{O}^{\Upsilon(nS)}(^3S_1^{[1]})\rangle\mathrm{Br}(\Upsilon(nS)\to\Upsilon(1S)),\\
\langle\mathcal{O}(^3P_1^{[1]})\rangle &= \sum_{n=1,2}\langle\mathcal{O}^{\chi_{b1}(nP)}(^3P_1^{[1]})\rangle\mathrm{Br}(\chi_{b1}(nP)\to\Upsilon(1S)),\\
\langle\mathcal{O}(^3P_2^{[1]})\rangle &= \sum_{n=1,2}\langle\mathcal{O}^{\chi_{b2}(nP)}(^3P_2^{[1]})\rangle\mathrm{Br}(\chi_{b2}(nP)\to\Upsilon(1S)),\\
\langle\mathcal{O}(^3S_1^{[8]})\rangle &= \langle\mathcal{O}^{\Upsilon(1S)}(^3S_1^{[8]})\rangle + \sum_{n=2,3}\langle\mathcal{O}^{\Upsilon(nS)}(^3S_1^{[8]})\rangle\mathrm{Br}(\Upsilon(nS)\to\Upsilon(1S))\\
&\quad + \sum_{n=1,2}\sum_{J=1,2}\langle\mathcal{O}^{\chi_{bJ}(nP)}(^3S_1^{[8]})\rangle\mathrm{Br}(\chi_{bJ}(nP)\to\Upsilon(1S)),\\
\langle\mathcal{O}(^1S_0^{[8]})\rangle &= \langle\mathcal{O}^{\Upsilon(1S)}(^1S_0^{[8]})\rangle + \sum_{n=2,3}\langle\mathcal{O}^{\Upsilon(nS)}(^1S_0^{[8]})\rangle\mathrm{Br}(\Upsilon(nS)\to\Upsilon(1S)),\\
\langle\mathcal{O}(^3P_0^{[8]})\rangle &= \langle\mathcal{O}^{\Upsilon(1S)}(^3P_0^{[8]})\rangle + \sum_{n=2,3}\langle\mathcal{O}^{\Upsilon(nS)}(^3P_0^{[8]})\rangle\mathrm{Br}(\Upsilon(nS)\to\Upsilon(1S)).
\end{aligned} \tag{2}$$

Here the $\chi_{b0}(1P, 2P)$ feed down into $\Upsilon(1S)$ is ignored due to the smallness of the transition branching ratios. The potential model results of wave functions and their derivatives at the origin can be chosen as [33]

$$\begin{aligned}
&|R_{\Upsilon(1S)}(0)|^2 = 6.477\ \mathrm{GeV}^3, \qquad |R_{\Upsilon(2S)}(0)|^2 = 3.234\ \mathrm{GeV}^3, \qquad |R_{\Upsilon(3S)}(0)|^2 = 2.474\ \mathrm{GeV}^3,\\
&|R'_{\chi_b(1P)}(0)|^2 = 1.417\ \mathrm{GeV}^5, \qquad |R'_{\chi_b(2P)}(0)|^2 = 1.653\ \mathrm{GeV}^5,
\end{aligned} \tag{3}$$

and the CS LDMEs can be estimated by

$$\langle\mathcal{O}^{\Upsilon(nS)}(^3S_1^{[1]})\rangle = \frac{3}{4\pi}|R_{\Upsilon(nS)}(0)|^2, \qquad \langle\mathcal{O}^{\chi_{bJ}(nP)}(^3P_J^{[1]})\rangle = \frac{3}{4\pi}|R'_{\chi_b(nP)}(0)|^2(2J+1). \tag{4}$$

With the PDG data of branching ratios [34], we get

$$\langle\mathcal{O}(^3S_1^{[1]})\rangle = 1.81\ \mathrm{GeV}^3, \qquad \langle\mathcal{O}(^3P_1^{[1]})\rangle = 0.54\ \mathrm{GeV}^5, \qquad \langle\mathcal{O}(^3P_2^{[1]})\rangle = 0.62\ \mathrm{GeV}^5. \tag{5}$$

Now there leave only 3 unknown CO LDMEs: $\langle\mathcal{O}(^3S_1^{[8]})\rangle$, $\langle\mathcal{O}(^1S_0^{[8]})\rangle$, and $\langle\mathcal{O}(^3P_0^{[8]})\rangle$. They will be determined by fitting the Tevatron data [18,19]. Because they are nearly universal (up to a correction of order v^2 with calculated short-distance coefficients in the fit), the fitted results can be used to predict $\Upsilon(1S)$ production in other colliders.

IV. NUMERICAL RESULT

The CTEQ6L1 and CTEQ6M parton-distribution functions [35] are used for LO and NLO calculations, respectively. The bottom quark mass is set to be $m_b = 4.75$ GeV, while the renormalization, factorization, and NRQCD scales are $\mu_r = \mu_f = m_T$ and $\mu_\Lambda = m_b$, where $m_T = \sqrt{p_T^2 + 4m_b^2}$ is the Υ transverse mass. The center-of-mass energies are 1.8 TeV, 1.96 TeV and 7 TeV for the Tevatron RUN I, RUN II, and LHC, respectively.

In the fit we introduce a p_T^{cut}, and the Tevatron data [18,19] in Fig. 1 with $p_T > p_T^{\mathrm{cut}}$ are used to fit the 3 unknown CO LDMEs: $\langle\mathcal{O}(^3S_1^{[8]})\rangle$, $\langle\mathcal{O}(^1S_0^{[8]})\rangle$ and $\langle\mathcal{O}(^3P_0^{[8]})\rangle$. The reason for discarding the low p_T data is that these data are far from the large p_T region ($\frac{m_b}{p_T} \ll 1$), and may also be affected by nonperturbative effects, which can not be described by our fixed order perturbative calculation. If we choose too large p_T^{cut}, there are no enough data to determine the CO LDMEs, so we choose $p_T^{\mathrm{cut}} = 8$ GeV. Anyway, by varying p_T^{cut} from 7 GeV to 9 GeV, we find the determined CO LDMEs in Eq. (12) are roughly consistent within errors. As discussed in Refs. [12,14], by fitting large p_T data at the Tevatron one can only constrain two linear combinations of LDMEs that have p_T^{-4} and p_T^{-6} behaviors at parton level, respectively. Thus, to have a constrained fit, the short-distance coefficient of P-wave channel is decomposed into linear combination of that of two S-wave channels in Ref. [12], and as a result, one needs to fit only two linear combinations of LDMEs (M_0 and M_1). However, for Υ production we find the decomposition of P-wave channel is good only for $p_T > 15$ GeV, thus, to fit the Tevatron data with $p_T \gtrsim 8$ GeV, we cannot decompose the P-wave channel. Therefore, we fit the three LDMEs using a similar method described in Ref. [14].

Define

$$O_1 \equiv \langle\mathcal{O}(^1S_0^{[8]})\rangle, \qquad O_2 \equiv \langle\mathcal{O}(^3S_1^{[8]})\rangle, \qquad O_3 \equiv \frac{\langle\mathcal{O}(^3P_0^{[8]})\rangle}{m_b^2}, \tag{6}$$

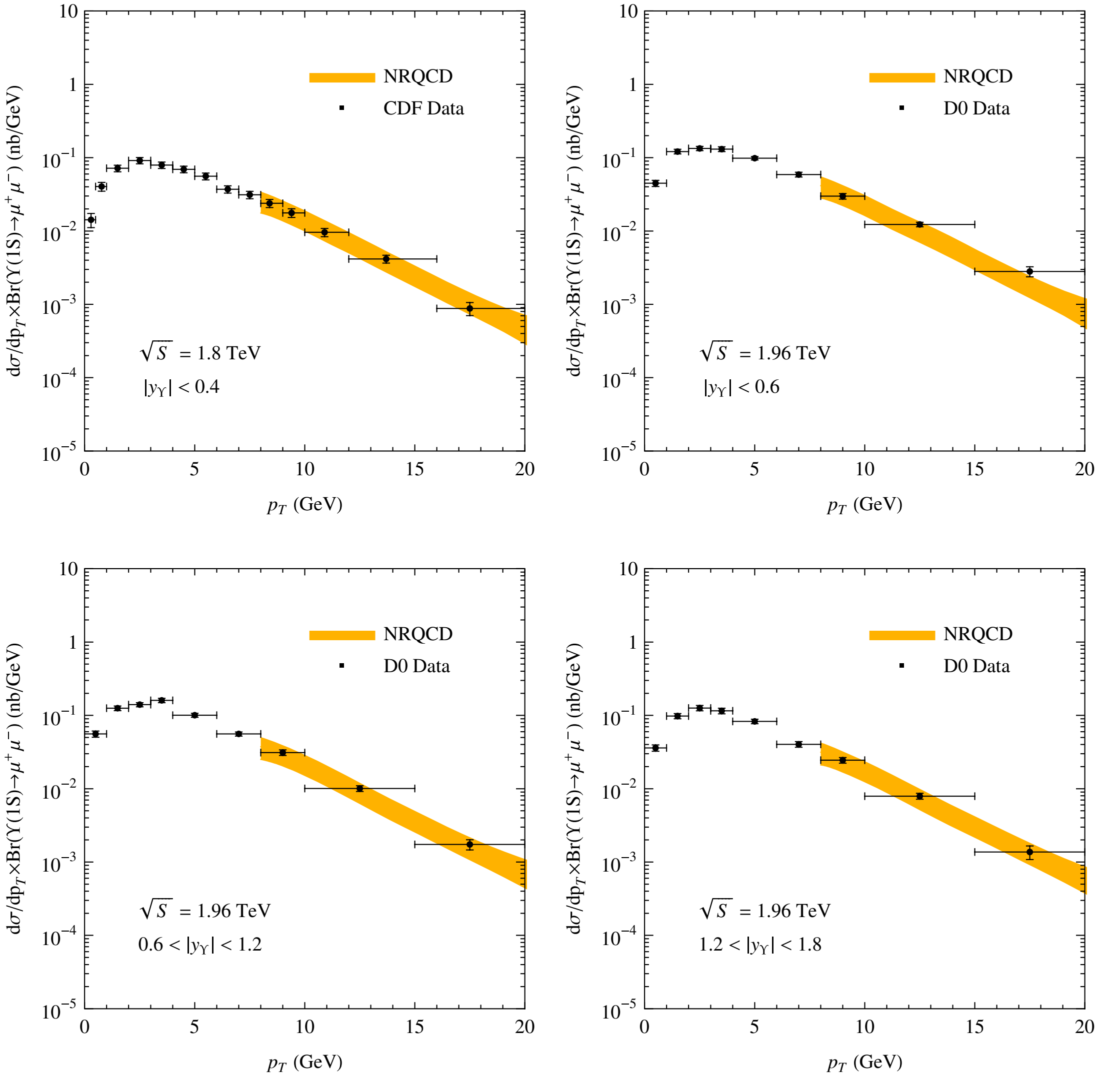

FIG. 1 (color online). Transverse momentum distributions of prompt $\Upsilon(1S)$ production cross sections at the Tevatron. The CDF data are taken from Ref. [18]. The D0 data are taken from Ref. [19].

and the correlation matrix C

$$C_{ij}^{-1} = \frac{1}{2}\frac{d^2\chi^2}{dO_i dO_j}. \tag{7}$$

By minimizing χ^2 we have

$$C = \begin{pmatrix} 0.24 & -0.024 & -0.54 \\ -0.024 & 0.0025 & 0.054 \\ -0.54 & 0.054 & 1.21 \end{pmatrix}. \tag{8}$$

The eigenvalues λ_i with corresponding eigenvectors $\mathbf{v}_i$ of C are

$$\begin{aligned} \lambda_1 &= 1.5, & \vec{\mathbf{v}}_1 &= (-0.41, 0.040, 0.91) \\ \lambda_2 &= 3.5\times 10^{-4}, & \vec{\mathbf{v}}_2 &= (0.79, -0.48, 0.38) \\ \lambda_3 &= 1.3\times 10^{-5}, & \vec{\mathbf{v}}_3 &= (0.46, 0.87, 0.17). \end{aligned} \tag{9}$$

The LDMEs corresponding to the eigenvectors are

$$\begin{pmatrix} \Lambda_1 \\ \Lambda_2 \\ \Lambda_3 \end{pmatrix} = V \begin{pmatrix} O_1 \\ O_2 \\ O_3 \end{pmatrix}, \tag{10}$$

where we denote matrix

$$V = \begin{pmatrix} \vec{\mathbf{v}}_1 \\ \vec{\mathbf{v}}_2 \\ \vec{\mathbf{v}}_3 \end{pmatrix}. \tag{11}$$

Inserting Eqs. (6) and (9) into Eq. (10), we have

$$\begin{aligned} \Lambda_1 &= -274\times 10^{-2}\ \mathrm{GeV}^3(\pm 44\%), \\ \Lambda_2 &= 6.04\times 10^{-2}\ \mathrm{GeV}^3(\pm 31\%), \\ \Lambda_3 &= 10.5\times 10^{-2}\ \mathrm{GeV}^3(\pm 3.4\%). \end{aligned} \tag{12}$$

In this way, the three CO LDMEs are expressed in terms of their linear combinations Λ_i, which correspond to the eigenvectors of the correlation matrix. As the Tevatron

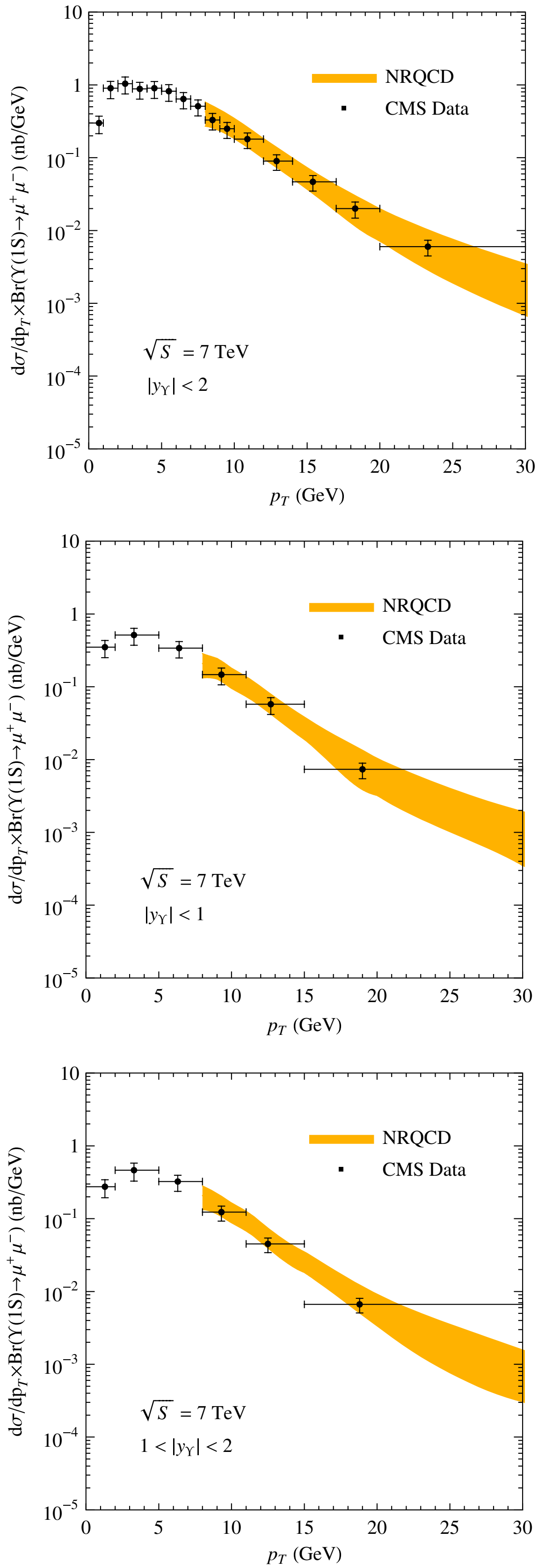

FIG. 2 (color online). Transverse momentum distributions of prompt $\Upsilon(1S)$ production cross sections at the LHC. The CMS data are taken from Ref. [26].

data are not sensitive to the value of Λ_1 in our fit, there is a large range value of Λ_1 that can satisfy the data, and its determined value in the fit is just randomly chosen from this range. If the range is much larger than the physical value of Λ_1, there will be a high possibility that the absolute value of its fitted value is much larger than its physical value. Assuming the physical value of Λ_1, Λ_2 and Λ_3 are of the same order, the random choice implies the absolute value of the fitted value of Λ_1 will be much larger than Λ_2 and Λ_3, which is the case in our fit. Nevertheless, to change Λ_1 to be the same order as Λ_2 and Λ_3, one needs more than two σ shift. It implies results in Eq. (12) may underestimate the error of Λ_1.

Values of Λ_i contain main result in our fit. To use them to predict $\Upsilon(1S)$ production in other experiment, we express the differential cross section as

$$d\sigma = \sum_{i=1}^{3} d\hat{\sigma}_i O_i = \sum_{i=1}^{3} a_i \Lambda_i, \quad \text{with} \quad \vec{\mathbf{a}} = \overrightarrow{d\hat{\sigma}} V^{-1}, \tag{13}$$

where $d\hat{\sigma}_i$ denote corresponding short-distance coefficients. In this form, the errors induced by Λ_i can be easily taken into consideration for they are independent. Based on Eq. (13), our predictions for CMS and LHCb are plotted in Fig. 2 and 3, respectively, where CMS and LHCb data are taken from Refs. [26,27]. The uncertainties of the curves concern the renormalization scale dependence in the calculation and the errors from Λ_i. We treat these two types of uncertainties as independent ones. From these figures, we can see that our predictions are consistent with the LHC experimental data, which is an explicit demonstration of the universality of LDMEs defined in Eq. (3).

V. SUMMARY

In summary, we calculate the complete NLO corrections for the $\Upsilon(1S)$ production at hadron colliders up to $\mathcal{O}(\alpha_s^4 v^4)$. Ignoring corrections of higher-orders in v^2, we combine the production LDMEs of $\Upsilon(1S)$ and other excited states into 3 color-singlet LDMEs and 3 color-octet LDMEs. These 6 LDMEs are approximately universal and they include almost all feed-down contributions to $\Upsilon(1S)$ production. The CS LDMEs are estimated by using potential model results, while the CO LDMEs are determined by fitting the Tevatron data. Then we find our predictions well coincide with the new experimental data at the LHC. Our work may provide a new test for the universality of LDMEs in $\Upsilon(1S)$ hadroproduction.

To have a comprehensive understanding of $\Upsilon(1S)$ hadroproduction, it is certainly important to also compare the theoretical result with the polarization data for $\Upsilon(1S)$, we leave it as a further study. Encouraged by the result of J/ψ polarization [16], where we find the J/ψ polarization and yield can be consistently explained by two well constrained CO LDMEs (M_0 and M_1), a good description for the $\Upsilon(1S)$ data including yield and polarization seems to be

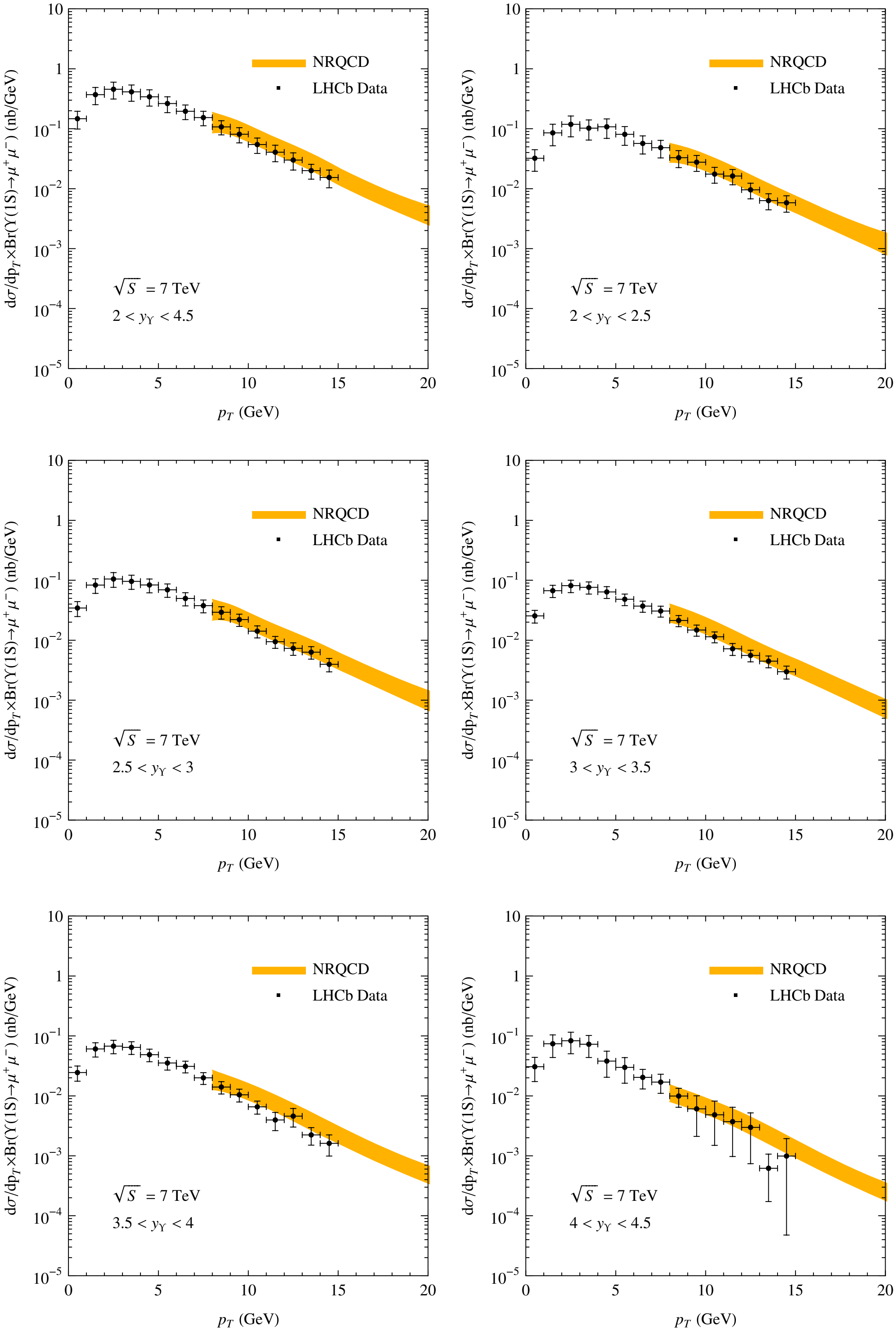

FIG. 3 (color online). Transverse momentum distributions of prompt $\Upsilon(1S)$ production cross sections at the LHC. The LHCb data are taken from Ref. [27].

promising. However, note that the values of two well constrained CO LDMEs in J/ψ production are significantly different [12,14], while for $\Upsilon(1S)$ production we find from Eq. (12) that Λ_2 and Λ_3 are of the same order. Another complexity concerns the influence of big feed-down contributions on $\Upsilon(1S)$ polarization. Therefore, a full understanding of $\Upsilon(1S)$ production including both yield and polarization may provide important information in addition to the study of J/ψ production. On the experiment side, because the bottom quark is heavy: $m_b \approx 5$ GeV, to test the large p_T ($\frac{m_b}{p_T} \ll 1$) behavior one needs to measure the cross sections and polarizations at p_T as large as, say 30 GeV and even larger, with higher statistics, and to separate the higher excited $b\bar{b}$ production from the $\Upsilon(1S)$ production. This is a hard task for experiment, and we hope it can be fulfilled at the LHC in the near future. Then we can make more thorough comparison between theory and experiment, and provide a further test of NRQCD factorization.

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