Study of bottomonium production cross-section in pp collisions at LHC energies using NRQCD

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Introduction

Quarkonia are bound states of either a charm and anti-charm quark pair (charmonia, e.g. J/ψ, χ_c and $\psi(2\mathrm{S})$) or a bottom and anti-bottom quark pair (bottomonia, e.g. $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, χ_b and $\Upsilon(3\mathrm{S})$). The quarkonia production mechanism in pp collisions is qualitatively understood by the models based on the Quantum Chromodynamics(QCD), in particular, in the non-relativistic QCD (NRQCD) [1, 2]. The quarkonia production in NRQCD is a two step process: First, the creation of the $Q\bar{Q}$ pair in a hard scattering at short distances which are process-dependent, is to be calculated perturbatively as an expansions in the strong coupling constant α_s. Note that $Q\bar{Q}$ states can be in the color-singlet(CS) [3] as well as in a color-octet(CO) [4] states. Second, the $Q\bar{Q}$ pair evolves into the quarkonium state with the probabilities that are given by the supposedly universal nonperturbative long-distance matrix elements (LDMEs) which have to be extracted from experiments. For CO states, this evolution process also involves the nonperturbative emission of soft gluons to form a CS states. The crucial feature of this formalism is that the complete structure of the $Q\bar{Q}$ Fock space, which is spanned by the states $n = {}^{2S+1}L_J^{[i]}$ with spin S, orbital angular momentum L, total angular momentum J, and color multiplicity $i = 1, 8$.

According to the NRQCD factorization formalism [1, 2], the cross section for direct production of a resonance H in a collision of particle A and B can be expressed as

$$d\sigma_{A+B\to H+X} = \sum_{i,j,n}\int dx_a dx_b G_{a/A}(x_a,\mu_F) \\ G_{b/B}(x_b,\mu_F) d\sigma(a+b\to Q\bar{Q}(n)+X)\left\langle \mathcal{O}^H(n)\right\rangle \quad (1)$$

where $G_{a/A}(G_{b/B})$ is the partonic distribution function(PDF) of the incoming partons $a(b)$ in the incident hadron $A(B)$ which depends on the large light-cone momentum fraction $x_a(x_b)$ and the factorization scale μ_F. The short distance contribution $d\sigma(a+b\to Q\bar{Q}(n)+X)$ can be calculated within the framework of perturbative QCD(pQCD). On the other hand, $\left\langle \mathcal{O}^H(n)\right\rangle$ are nonperturbative LDMEs and to be extracted from experiment.

Results

The NRQCD calculations have been carried out for the differential cross-section of $\Upsilon(\mathrm{nS})$ as a function of p_T in pp collisions at $\sqrt{s} = 7$ TeV. The numerical values from the NRQCD calculations for differential cross-section of $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ as a function of p_T have been compared with the experimental results obtained by ATLAS ($|y| < 1.2$) [5] and LHCb ($2 < y < 4.5$) [6] are shown in the top, middle and bottom panel of Fig 1, respectively. This detail study explores the validity of NRQCD calculations at mid and forward rapidities at LHC energies. There are various feed-down contributions in Υ production and some of them are ignored in our calculations where the contribution are negligible. The feed-down contributions considered in the present calculations are: (i) for $\Upsilon(2\mathrm{S})$, feed-down contributions from $\Upsilon(3\mathrm{S})$ and $\chi_{bJ}(2P)$ are included; (ii) the feed-down contributions from $\Upsilon(2\mathrm{S})$, $\Upsilon(3\mathrm{S})$, $\chi_{bJ}(1P)$ and $\chi_{bJ}(2P)$ are included for $\Upsilon(1\mathrm{S})$. No feed-down contribution is included for $\Upsilon(3\mathrm{S})$.

In order to estimate the uncertainty on the calculated values, four possible sources have been considered, namely the perturbative scales, the mass of the bottom quark, the branching ratios for the feed-down to Υ and the PDFs. The uncertainty due to the assumed PDF was estimated by performing the calculations with different PDFs, namely CTEQ6L and CTEQ6L1. The uncertainty related to the choice of the heavy quark masses was estimated by varying them in the ranges $4.5 < m_b < 5$ GeV. We define the renormalization and factorization scales by $\mu_{R,F} = \xi_{R,F}\mu_0$, where μ_0 is $\sqrt{p_\mathrm{T}^2 + m_b^2}$. The central values of our predictions are obtained with $\xi_{R,F} = 1$, the mass of the bottom quark $m_b = 4.75$ GeV. To avoid the accidental compensation between the μ_F and μ_R dependence of the cross-section occurring when the two scales are kept equal, we compute the scale uncertainty by varying μ_F and μ_R independently over the range $0.5 < \xi_{R,F} < 2$, with the constraint $0.5 < \xi_R/\xi_F < 2$. The uncertainty due to this scale variation is the dominant source of uncertainy. All the uncertainties are added in quadrature.

Summary

The inclusive production cross-section of $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ at LHC energies have been calculated within the framework of NRQCD. These calculations include the contributions from direct production and from the decays of heavier bottomoium states. The comparisons with ex-

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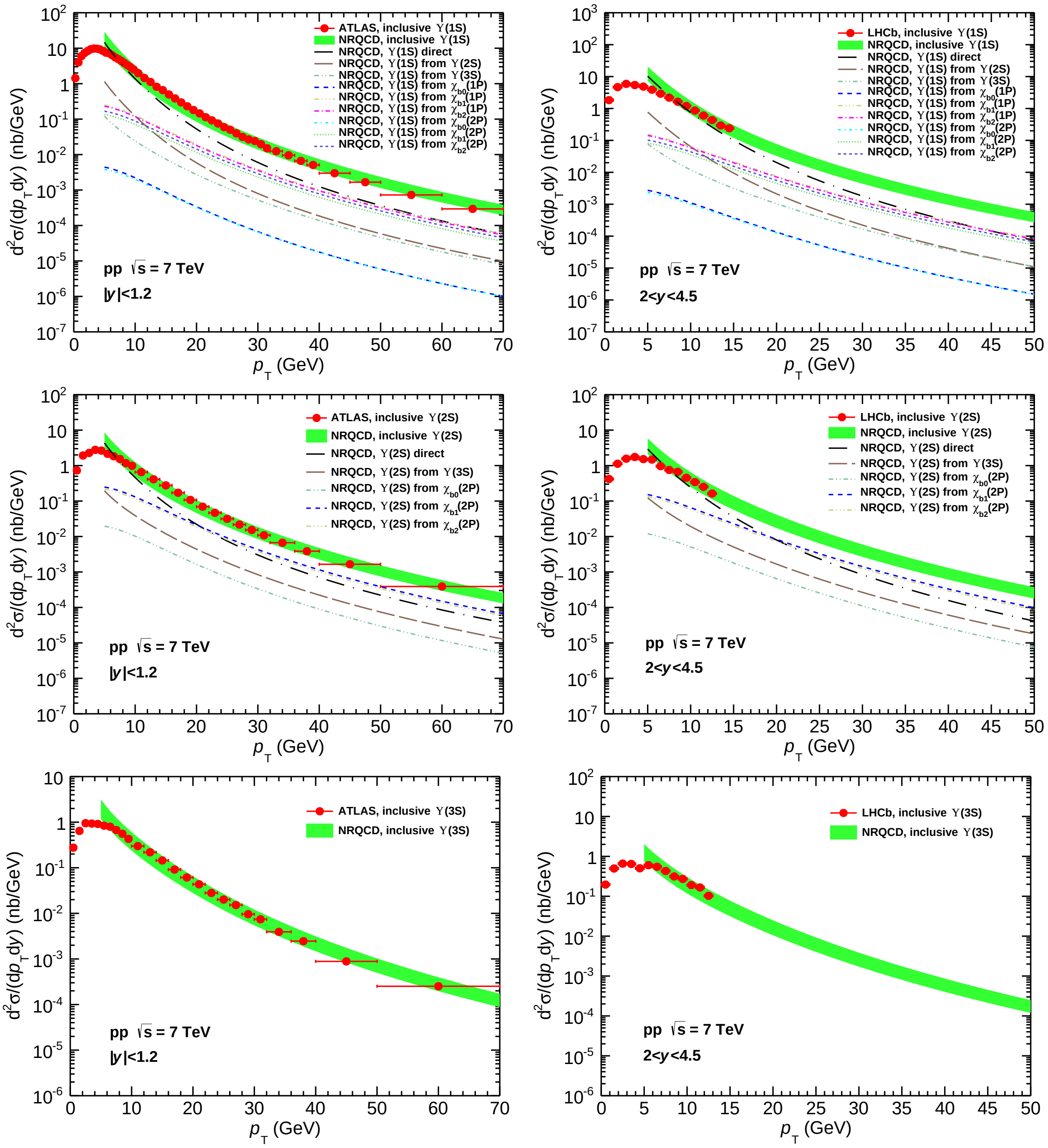

FIG. 1: Differential production cross-section of Υ(1S) (top panel), Υ(2S) (middle panel) and Υ(3S) (bottom panel) as a function of $p_{\rm T}$ compared with the ATLAS [5] and LHCb [6] data. The calculations corresponding to the sum of all contributions are shown as a green band. The direct and feed-down contributions from heavier bottomoium states are shown only by lines for the central values.

perimental data from LHC show that the NRQCD calculations give a good description of the bottomonium production cross-sections for $p_{\rm T} > 5$ GeV.

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