

High p_T $\Upsilon(3S)$ production at LHC energies

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Introduction

The quarkonia ($Q\bar{Q}$) have provided useful tools for probing both perturbative and non-perturbative aspects of Quantum Chromodynamics (QCD). The quarkonia states are qualitatively different from most other hadrons since the velocity of the heavy constituents is small allowing a non-relativistic treatment of bound states. The NRQCD formalism is one of the most promising theoretical framework for the study of heavy quarkonium production [1]. The study of the differential charmonia production cross sections in high energy p+p collisions is completed using NRQCD formalism [2].

Bottomonia Production in p+p collisions

Under NRQCD, the cross-section for direct production of a resonance H in a collision of particles A and B can be expressed in factorized form

$$E \frac{d^3\sigma^{ab \rightarrow cd}}{d^3p} ({}^{(2S+1)}L_J) = \sum_{a,b} \int dx_a dx_b G_{a/A}(x_a, \mu_F^2) G_{b/B}(x_b, \mu_F^2) \frac{\hat{s}}{\pi} \frac{d\sigma}{d\hat{t}} (ab \rightarrow {}^{(2S+1)}L_J c) \cdot \delta(\hat{s} + \hat{t} + \hat{u} - M^2)$$

where, $G_{a/A}(G_{b/B})$ is the parton distribution function (PDF) of the incoming parton $a(b)$ in the incident hadron $A(B)$, which depends on the momentum fraction $x_a(x_b)$ and the factorization scale μ_F . The short distance contribution $d\sigma/d\hat{t}$ can be calculated within the framework of perturbative QCD (pQCD). $(ab \rightarrow {}^{(2S+1)}L_J c)$ represents the probability of evolving a bound quarkonia state from a

$Q\bar{Q}$ pair. These probabilities (LDMEs) should be estimated from the experimental measurements. In this work the production cross section of $b\bar{b}$ bound states is calculated in p+p collisions $\sqrt{s} = 7$ TeV and measured data from CMS and ATLAS collaborations [3, 4] is used to constrain the LDMEs required for $\Upsilon(3S)$ production.

The LDMEs are predicted to scale with a definite power of the relative velocity v of the heavy constituents inside $Q\bar{Q}$ bound states. In the limit $v \ll 1$, the production of quarkonium is based on the ${}^3S_1^{[1]}$ and ${}^3P_J^{[1]}$ ($J = 0, 1, 2$) Color Singlet states, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ Color Octet states. The differential cross section for the direct production of $\Upsilon(3S)$ can be written as the sum of these contributions,

$$\begin{aligned} d\sigma(\Upsilon(3S)) = & d\sigma(Q\bar{Q}([{}^3S_1]_1)) M_L([{}^3S_1]_1) \\ & + d\sigma(Q\bar{Q}([{}^1S_0]_8)) M_L([{}^1S_0]_8) \\ & + d\sigma(Q\bar{Q}([{}^3S_1]_8)) M_L([{}^3S_1]_8) \\ & + d\sigma(Q\bar{Q}([{}^3P_J]_8)) M_L([{}^3P_0]_8) \end{aligned}$$

In our calculations, we used the expressions for the short distance cross-sections from Refs. [9, 10].

Results and discussion

$\Upsilon(3S)$ is the highest known bound state in the $b\bar{b}$ spectrum so it must not have any feed down contribution. The expressions and the values for the color-singlet LDMEs can be obtained by solving the non-relativistic wavefunctions [10]. The CO LDMEs can not be related to the non-relativistic wavefunctions of $b\bar{b}$ since it involves a higher Fock state and thus measured data from different experimental collaborations are used to constrain them. Figure 1 shows the NRQCD calculations of production cross section of $\Upsilon(3S)$ in p+p collisions as a function of transverse momentum

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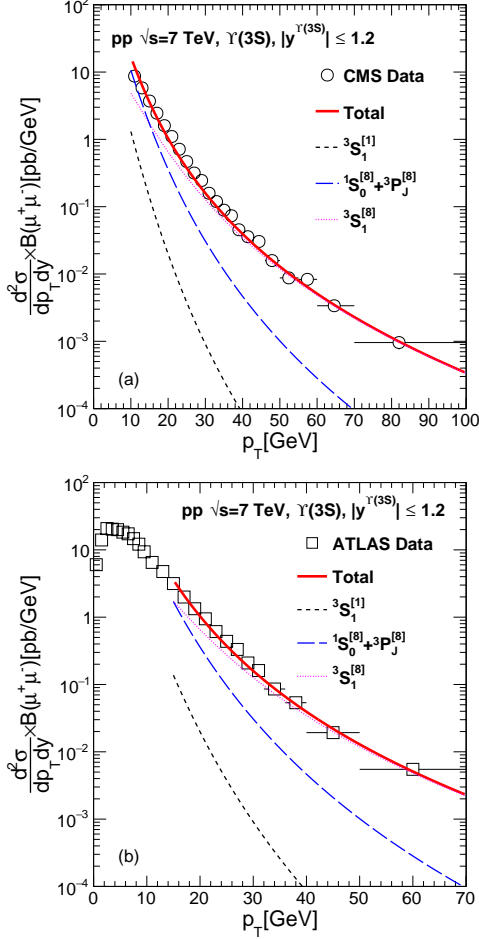


FIG. 1: The NRQCD calculations of production cross section of $\Upsilon(3S)$ in p+p collisions at $\sqrt{s} = 7$ TeV central rapidities, as a function of transverse momentum compared with the measured data at CMS [3] and ATLAS [4] experiment.

compared with the measured data in CMS [3] and ATLAS [3] detectors at LHC at central rapidities. In Figure 2, similar comparisons have been shown with data for $1.2 < |y| < 2.25$ and $|y| < 2.4$ measured at ATLAS [4] and CMS [5] detectors respectively. Figure 3 corresponds to CMS [6] detections at $\sqrt{s}=13\text{TeV}$ for centralities, $|y| < 0.6$, $0.6 < |y| < 1.2$ and $|y| < 1.2$, whereas in Figure 4 we have used measurements from CDF [7] collaboration at

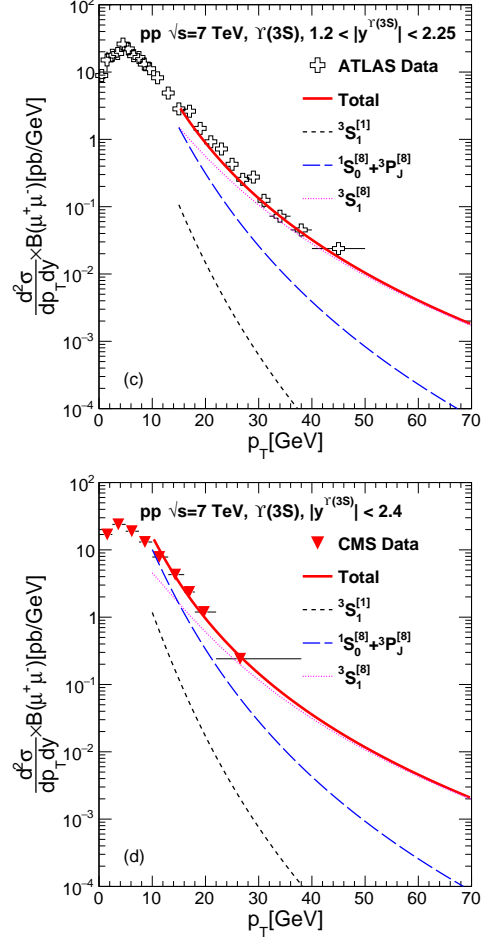


FIG. 2: The NRQCD calculations of production cross section of $\Upsilon(3S)$ in p+p collisions at $\sqrt{s} = 7$ TeV forward rapidities, as a function of transverse momentum compared with the measured data at ATLAS [4] and CMS [5] experiments.

$\sqrt{s}=1.8\text{TeV}$ and $|y| < 0.4$ as well as that from LHCb [8] collaboration at $\sqrt{s}=7\text{TeV}$ and $2.0 < |y| < 2.5$. The LDMEs are obtained by a combined fit using all the aforesaid dataset. The color-singlet contribution along with the calculated value and color-octet contributions fitted from data are given below for the $\Upsilon(3S)$

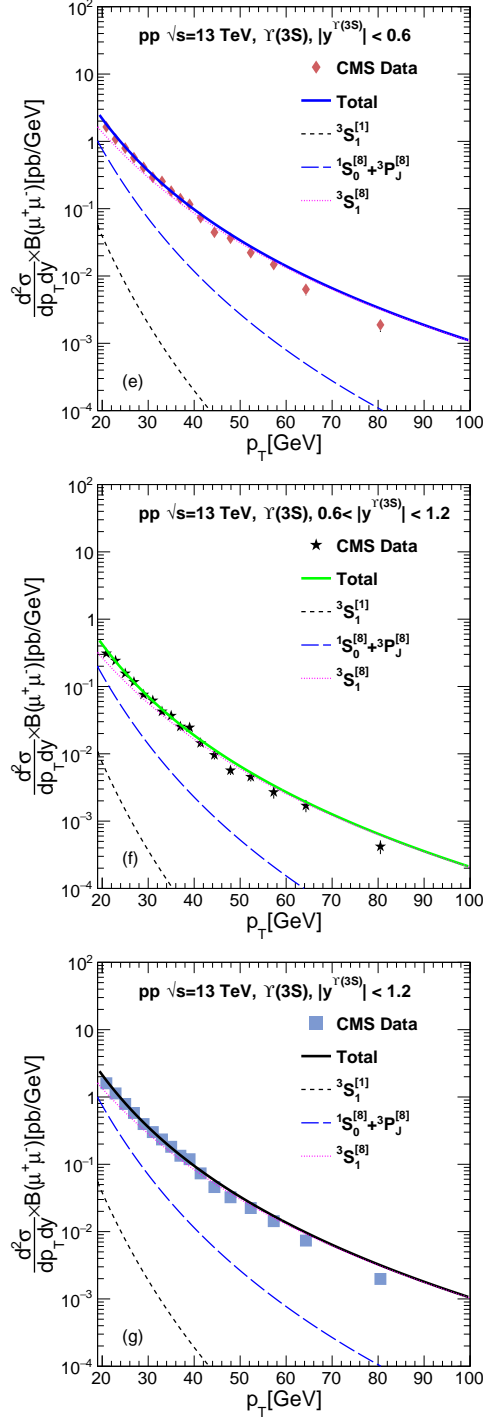


FIG. 3: The NRQCD calculations of production cross section of $\Upsilon(3S)$ in p+p collisions at $\sqrt{s} = 13$ TeV central and forward rapidities, as a function of transverse momentum compared with the measured data at CMS [6] experiment.

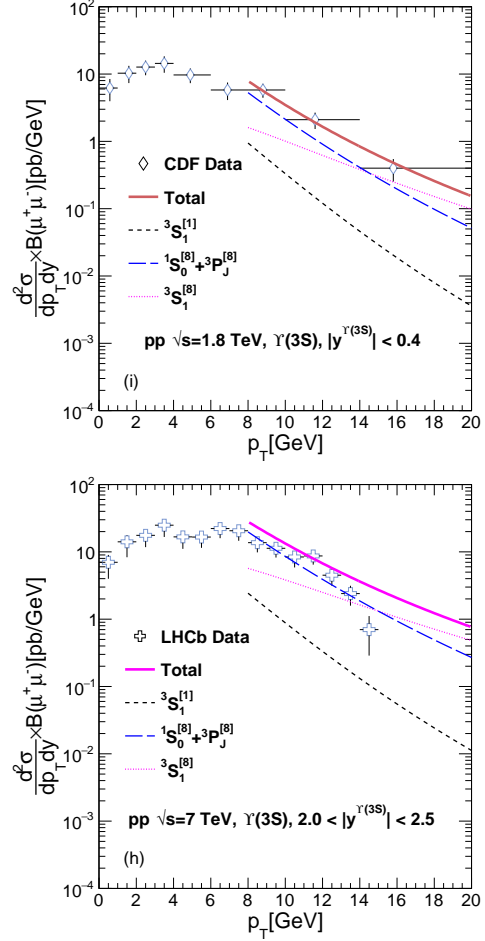


FIG. 4: The NRQCD calculations of production cross section of $\Upsilon(3S)$ in p+p collisions at $\sqrt{s} = 1.8$ and 7 TeV forward rapidities, as a function of transverse momentum compared with the measured data at CDF [7] and LHCb [8] experiment.

production.

$$\begin{aligned}
 M_L([{}^3S_1]_1) &= 4.3 \text{ GeV}^3 \\
 M_L([{}^3S_1]_8) &= (0.0570881 \pm 0.0007) \text{ GeV}^3 \\
 M_L([{}^1S_0]_8) &= (0.0187768 \pm 0.0005) \text{ GeV}^3 \\
 &= M_L([{}^3P_0]_8)/5m_b^2 \text{ GeV}^3
 \end{aligned}$$

The combined fitting of CMS, ATLAS, CDF and LHCb data at different collision energies

and at different rapidity intervals is done to extract common color octet LDMEs to explain all the datasets simultaneously. The χ^2/dof is 4.02032 for the combined fitting. Our value of $M_L([{}^3S_1]_8)$ is compatible with the value obtained in the recent calculations [11] while the value of $M_L([{}^1S_0]_8)$ is larger than the value of Ref. [11]. We have however significantly improved the large ($\approx 300\%$) error present on the value of $M_L([{}^1S_0]_8)$ in Ref. [11].

Summary

We have calculated the differential production cross-section of $\Upsilon(3S)$ meson as a function of transverse momentum. The data from LHC experiments are used to obtain the values of color octet LDMEs. We plan to present a rigorous study of production of all states of bottomonia at LHC energies using NRQCD. The reevaluation of all LDMEs required for bottomonia production is in progress using latest data from LHC.

References

- [1] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D **51** 1125 (1995), [Erratum-ibid. D **55** 5853 (1997)].
- [2] V. Kumar and P. Shukla, arXiv:1606.08265 [hep-ph].
- [3] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **749**, 14 (2015), [arXiv:1501.07750 [hep-ex]].
- [4] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **87**, no. 5, 052004 (2013), [arXiv:1211.7255 [hep-ex]].
- [5] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **727**, 101-125 (2013), [arXiv:1303.5900 [hep-ex]].
- [6] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **780**, 251-272 (2018), [arXiv:1710.11002 [hep-ex]].
- [7] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **88**, 161802 (2002).
- [8] R. Aaij *et al.* [LHCb Collaboration], Euro. Phys. Jour. C **72**, 2025 (2012), [arXiv:1202.6579 [hep-ex]].
- [9] R. Baier and R. Ruckl, Z. Phys. C **19**, 251 (1983).
- [10] P. L. Cho and A. K. Leibovich, Phys. Rev. D **53**, 150 (1996).
- [11] R. Sharma and I. Vitev, Phys. Rev. C **87**, 044905 (2013).