Quarkonia production and dissociation in Pb+Pb collisions

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Abstract

We calculate the high p_T quarkonia production using NRQCD method. Different methods of quarkonia suppression are used to explain the high p_T quarkonia suppression obseved by CMS in LHC

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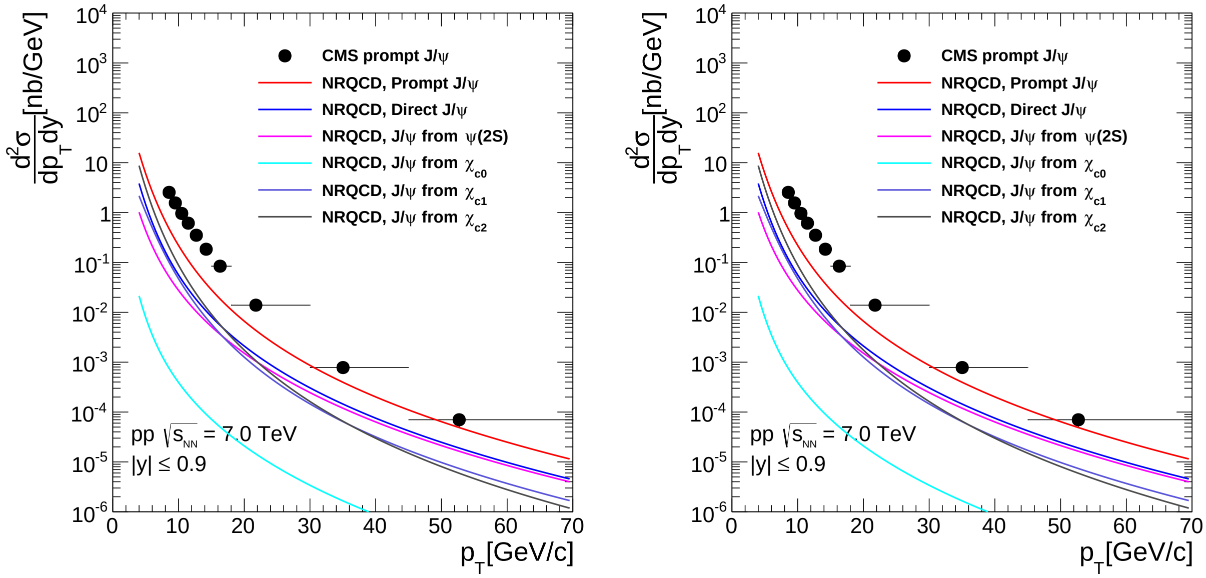

FIG. 1. (Color online) Differential production cross-section of J/ψ as a function of p_T compared with the CMS [?] data.

I. INTRODUCTION

Heavy-ion collisions at relativistic energies are performed to create and characterize quark gluon plasma (QGP), a phase of strongly-interacting matter at high energy density where quarks and gluons are no longer bound within hadrons. The quarkonia states (J/ψ and Υ) have been some of the most popular tools since their suppression was proposed as a signal of QGP formation [1]. The understanding of these probes has evolved substantially via measurements through three generations of experiments: the SPS (at CERN), RHIC (at BNL) and the LHC (at CERN) and by a great deal of theoretical activity. (For recent reviews see Refs. [2–4].) Quarkonia are produced early in the heavy-ion collisions and, if they evolve through the deconfined medium, their yields should be suppressed in comparison with those in *pp* collisions. The first such measurement was the 'anomalous' J/ψ suppression discovered at the SPS which was considered to be a hint of QGP formation. The RHIC measurements showed almost the same suppression at a much higher energy contrary to expectation [4, 5]. Such an observation was consistent with the scenario that, at higher collision energies, the expected greater suppression is compensated by J/ψ regeneration through recombination of two independently-produced charm quarks [6].

In this paper, we calculate J/ψ and Υ production and suppression

II. QUARKONIA PRODUCTION IN P+P COLLISIONS

In this section we describe the production of quarkonia at high transverse momenta in p+p collisions.

The factorization formalism of the NRQCD provides a theoretical framework for studying the heavy quarkonium production and decay. According to the NRQCD factorization formalism, the cross-section for direct production of a resonance H in a collision of particle A and B can be expressed as

$$d\sigma_{A+B\to H+X} = \sum_{a,b,n} \int dx_a dx_b G_{a/A}(x_a,\, \mu_F^2)\, G_{b/B}(x_b,\, \mu_F^2) \times d\sigma(a+b \to Q\bar{Q}(n)+X) < \mathcal{O}^H(n) > \tag{1}$$

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 as well as on the renormalization scale μ_R. However, as we have chosen $\mu_F = \mu_R$, in our case PDFs are function of x and μ_F only. The tranverse mass of the resonance H is $m_T = \sqrt{p_T^2 + m_H^2}$, where $m_H \sim 2m_Q$ is the mass of resonance H. 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, $< \mathcal{O}^H(n) >$ (the state $n =^{2S+1} L_J^{[i]}$) are nonperturbative LDMEs and can be estimated on the basis of the comparison with experimental measurements.

The dominant processes in evaluating the differential yields of heavy mesons as a function of p_T are the $2 \to 2$ processes of the kind $g+q \to H+q$, $q+\bar{q} \to H+g$ and $g+g \to H+g$, where H refers to the heavy meson. We label the process generically as $a+b \to c+d$, where a and b are light incident partons, c refers to H and d is a light final-state parton. The differential cross-section for the short distance contribution i.e. the heavy quark pair production from the reaction of the type $a + b \to c + d$ can be written as [7]

$$\frac{d\sigma^{ab\to cd}}{dp_T\, dy} = \int dx_a\, G_{a/A}(x_a,\, \mu_F^2)\, G_{b/B}(x_b,\, \mu_F^2) \times 2p_T \frac{x_a\, x_b}{x_a - \frac{m_T}{\sqrt{s}} e^y} \frac{d\sigma}{d\hat{t}}(ab \to cd), \tag{2}$$

where, $\sqrt{s}$ being the total energy in the centre-of-mass and y is the rapidity of the $Q\bar{Q}$ pair. In our numerical computation, we use CTEQ6M [8] for the parton distribution functions. The invariant differential cross-section is given by

$$\frac{d\sigma}{d\hat{t}} = \frac{|\mathcal{M}|^2}{16\pi\hat{s}^2}, \tag{3}$$

where $\hat{s}$ and $\hat{t}$ are the parton level Mandelstam variables. $\mathcal{M}$ is the feynman amplitude for the process. Energy momentum conservation fixes value of the momentum fraction x_b as,

$$x_b = \frac{1}{\sqrt{s}} \frac{x_a \sqrt{s}\, m_T\, e^{-y} - m_H^2}{x_a \sqrt{s} - m_T\, e^{y}}. \tag{4}$$

The minimum value of x_a is

$$x_{a\min} = \frac{1}{\sqrt{s}} \frac{\sqrt{s}\, m_T\, e^{y} - m_H^2}{\sqrt{s} - m_T\, e^{-y}}. \tag{5}$$

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 $v << 1$, the production of quarkonium is based on the ${}^3S_1^{[1]}$ and ${}^3P_J^{[1]}$ (J = 0,1,2) CS states and ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ CO states. In our calculations, we used the expressions for the short distance CS cross-sections given in Refs. [9, 10] and the CO cross-sections given in Refs. [11, 12].

In this section we calculate the p_T distribution of J/ψ, $\psi(2S)$ and Υ(nS) mesons in $p-p$ collisions at LHC energies. For J/ψ production in $p-p$ collisions, three sources need to be considered: direct J/ψ production, feed-down contributions to the J/ψ from the decay of heavier charmonium states, predominantly from $\psi(2S)$, χ_{c0}, χ_{c1} and χ_{c2} and J/ψ from B hadron decays. The sum of the first two sources is called "prompt J/ψ" and the third source will be called "J/ψ from B". On the other hand, $\psi(2S)$ has no significant feed-down contributions from higher mass states. We call this direct contribution as "prompt $\psi(2S)$" to be consistent with the experiments. The other source to $\psi(2S)$ production is from B hadron decays and we call it "$\psi(2S)$ from B". The sum of the prompt $J/\psi(\psi(2S))$ and $J/\psi(\psi(2S))$ from B will be called "inclusive $J/\psi(\psi(2S))$". Similar terminology is used for Υ states, only differnce is that we do not have any contribution from open T mesons.

NRQCD provides a systematic procedure to compute any quantity as an expansion in the relative velocity v of the heavy quarks in the meson. For example, the wavefunction of the J/ψ meson (analogous expressions hold for the $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$) is written as

$$\begin{aligned} |J/\psi\rangle =& |Q\bar{Q}([{}^3S_1]_1)\rangle + \mathcal{O}(v)|Q\bar{Q}([{}^1S_0]_8 g)\rangle + \mathcal{O}(v^2)|Q\bar{Q}([{}^3S_1]_8 gg)\rangle \\ &+ \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_0]_8 g)\rangle + \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_1]_8 g)\rangle + \mathcal{O}(v^1)|Q\bar{Q}([{}^3P_2]_8 g)\rangle + \cdots \end{aligned} \tag{6}$$

The differential cross section for the direct production of J/ψ can be written as the sum of the contributions,

$$\begin{aligned} d\sigma(J/\psi) = {} & d\sigma(Q\bar{Q}([^3S_1]_1))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_1) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^1S_0]_8))\langle\mathcal{O}(Q\bar{Q}([^1S_0]_8) \to J/\psi)\rangle \\ & + d\sigma(Q\bar{Q}([^3S_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_0]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_0]_8) \to J/\psi)\rangle \\ & + d\sigma(Q\bar{Q}([^3P_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_2]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_2]_8) \to J/\psi)\rangle + \cdots , \end{aligned} \tag{7}$$

where the quantity in the brackets [ ] represents the angular momentum quantum numbers of the $Q\bar{Q}$ pair in the Fock expansion. The subscript on [ ] refers to the color structure of the $Q\bar{Q}$ pair, 1 being the color-singlet and 8 being the color-octet. The dots represent terms which contribute at higher powers of v. The short distance cross sections $d\sigma(Q\bar{Q})$ correspond to the production of a $Q\bar{Q}$ pair in a particular color and spin configuration, while the long distance matrix element $\langle\mathcal{O}(Q\bar{Q}) \to J/\psi\rangle$ corresponds to the probability of the $Q\bar{Q}$ state to convert to the quarkonium wavefunction. This probability includes any necessary prompt emission of soft gluons to prepare a color neutral system that matches onto the corresponding Fock component of the quarkonium wavefunction.

III. SUMMARY

IV. ACKNOWLEDGEMENT

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