

**$J/\Psi$  Production in  $pp$  Collisions at  $\sqrt{s} = 200$  GeV at the BNL Relativistic Heavy Ion Collider**Fred Cooper,<sup>1,\*</sup> Ming X. Liu,<sup>2,†</sup> and Gouranga C. Nayak<sup>3,‡</sup><sup>1</sup>National Science Foundation, Arlington, Virginia 22230, USA

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We study  $J/\psi$  production in  $pp$  collisions at BNL Relativistic Heavy Ion Collider (RHIC) within the PHENIX detector acceptance range using the color singlet and color octet mechanism which are based on perturbative QCD and nonrelativistic QCD. Here we show that the color octet mechanism reproduces the RHIC data for  $J/\psi$  production in  $pp$  collisions with respect to the  $p_T$  distribution, the rapidity distribution, and the total cross section at  $\sqrt{s} = 200$  GeV. The color singlet mechanism leads to a relatively small contribution to the total cross section when compared to the octet contribution.

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Understanding the  $J/\psi$  production mechanism in high energy hadronic collisions is an important topic in QCD and in collider physics. Two prominent mechanisms for  $J/\psi$  production at high energy colliders are (1) the color singlet mechanism [1,2] and (2) the color octet mechanism [3], both of which rely on perturbative QCD (pQCD) and nonrelativistic QCD (NRQCD). At Fermilab Tevatron energies, the color singlet mechanism was found to give too small a yield and the color octet mechanism for  $J/\psi$  production was then introduced [4,5]. It was shown that the color octet mechanism, with both parton fusion and parton fragmentation processes included, reproduced the Tevatron data [6]. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven is a unique facility that can collide unpolarized and polarized protons at  $\sqrt{s} = 200$  and 500 GeV as well as two heavy nuclei such as gold on gold. The unpolarized  $pp$  collision data serve as a baseline for understanding collective phenomena such as the production of a quark-gluon plasma that is expected in the heavy ion collisions as well as providing the necessary information needed to extract interference terms generated when considering polarized  $pp$  collisions. One of the key things to be measured in Au-Au collisions as well as in polarized  $pp$  collisions is  $J/\psi$  production. In relativistic heavy ion collisions,  $J/\psi$  suppression has been posited to be one of the major signatures of the production of the quark-gluon plasma [7]. In case of polarized  $pp$  collisions, the measurement of  $J/\psi$  production is an important ingredient in extracting the polarized gluon distribution function for the proton directly. For that reason, understanding the dominant mechanism of  $J/\psi$  production is important. Thus it is crucial to first determine the relative importance of color singlet and color octet contributions in the existing unpolarized proton-proton scattering data at RHIC energies. In this Letter, we will study  $J/\psi$  production in  $pp$  collisions at RHIC by using the color

singlet and color octet mechanism within pQCD and NRQCD. We will study the  $p_T$  distribution, rapidity distribution, and total cross section of the  $J/\psi$  production at  $\sqrt{s} = 200$  GeV  $pp$  collisions and compare those with the recent measurements by the PHENIX collaboration at RHIC [8].

In the color singlet mechanism,  $Q\bar{Q}$  is produced in the color singlet state with spin ( $S$ ) and orbital angular momentum ( $L$ ) which evolve into a bound state  $2S + 1L_J$  with relative velocity of  $Q\bar{Q}$  being very small compared to mass of the heavy quark. The non-perturbative wave functions are calculated from potential model or taken from the experiments.

The leading term in the  $p_T$  distribution for the cross section for  $J/\psi$  production first occurs at order  $\alpha_s^3$ . The  $p_T$  distribution for heavy quarkonium production in the color singlet mechanism is given by:

$$\begin{aligned} \frac{d\sigma}{dp_T}(AB \rightarrow J/\psi, \chi_J + X) \\ = \sum_{a,b} \int dy \int dx_a x_a f_{a/A}(x_a, Q^2) x'_b f_{b/B}(x'_b, Q^2) \\ \times \frac{2p_T}{x_a - \frac{M_T}{\sqrt{s}}} \frac{d\hat{\sigma}}{d\hat{t}}[ab \rightarrow (2S+1L_J)c], \end{aligned} \quad (1)$$

where

$$x'_b = \frac{1}{\sqrt{s}} \frac{x_b \sqrt{s} M_T e^{-y} - M^2}{x_b \sqrt{s} - M_T e^y}. \quad (2)$$

In the above equation,  $a, b, c$  are light quarks and gluons.  $f(x, Q^2)$  is the parton distribution function at longitudinal momentum fraction  $x$  and at factorization scale  $Q$ .  $M$  is the mass of the bound state quarkonium and  $M_T = \sqrt{p_T^2 + M^2}$ . The partonic level differential cross section  $\frac{d\hat{\sigma}}{d\hat{t}}[ab \rightarrow (2S+1L_J)c]$  contain the nonrelativistic wave

function  $|R(0)|^2$  (for direct  $J/\psi$  process) and its derivatives  $|R'(0)|^2$  (for  $\chi_J$  processes) at the origin [1]. For the nonrelativistic wave functions at the origin, we take the Buchmuller-Tye wave function [9]. The numerical value is [9]:  $|R(0)|^2 = 0.81 \text{ GeV}^3$ . For the derivative of the radial wave function at origin we use [10]:  $\frac{9}{2\pi} \frac{|R'(0)|^2}{M_c^4} = 15 \text{ MeV}$ .

In the color octet mechanism, the relativistic effects are taken into account, which are neglected in the color singlet case. In the color octet mechanism using an effective field theory called NRQCD, the dynamical gluon enters into Fock state decompositions of the quarkonium states. In NRQCD, the expansion is carried out in terms of the relative velocity  $v$  ( $v^2 \sim 0.23$  for  $C\bar{C}$  system and 0.1 for  $B\bar{B}$  system) of the  $Q\bar{Q}$  bound state. The NRQCD Lagrangian density is given by

$$\mathcal{L}_{\text{NRQCD}} = \mathcal{L}_{\text{light}} + \mathcal{L}_{\text{heavy}} + \mathcal{L}_{\text{correction}}. \quad (3)$$

In the above equation, light refers to light quarks and gluons, heavy refers to lowest order nonrelativistic heavy quarks part, and correction is higher order corrections in heavy quark sector. The explicit expressions for the three terms can be found in [4]. In NRQCD, the dynamical gluons enter into the Fock state decompositions of different physical states. The wave function of an  $S$ -wave orthoquarkonia state  $|\psi_Q\rangle$  is expanded as follows:

$$\begin{aligned} |\psi_Q\rangle = & O(1)|Q\bar{Q}[{}^3S_1^{(1)}]\rangle + O(v)|Q\bar{Q}[{}^3P_J^{(8)}]g\rangle \\ & + O(v^2)|Q\bar{Q}[{}^3S_1^{(1,8)}]gg\rangle + O(v^2)|Q\bar{Q}[{}^1S_0^{(8)}]g\rangle \\ & + O(v^2)|Q\bar{Q}[{}^3D_J^{(1,8)}]gg\rangle + \dots \end{aligned} \quad (4)$$

and the wave functions of a  $P$ -wave orthoquarkonium state  $|\chi_{QJ}\rangle$  have a similar expansion:

$$|\chi_{QJ}\rangle = O(1)|Q\bar{Q}[{}^3P_J^{(1)}]\rangle + O(v)|Q\bar{Q}[{}^3S_1^{(8)}]g\rangle + O(v^2)\dots \quad (5)$$

In the above equation, (1, 8) refers to singlet and octet states of the  $Q\bar{Q}$  pair. After a  $Q\bar{Q}$  is formed in its color octet state, it may absorb a soft gluon and transform into  $|\chi_{QJ}\rangle$  via Eq. (5) and then become a  $J/\psi$  by photon decay. The  $Q\bar{Q}$  pair in the color octet state can also emit two long wavelength gluons and become a  $J/\psi$  via Eq. (4) and so on. The nonperturbative matrix elements can be fitted from other experiments or can be determined from lattice calculations.

In the color octet mechanism, the  $p_T$  distribution differential cross section for  $J/\psi$  production is given by:

$$\begin{aligned} \frac{d\sigma}{dp_T}[AB \rightarrow \psi_Q(\chi_J) + X] \\ = \sum_{a,b} \int dy \int dx_a x_a f_{a/A}(x_a, Q^2) x_b' f_{b/B}(x_b', Q^2) \hat{E} \\ \times \frac{2p_T}{x_a - \frac{M_c}{\sqrt{s}} e^y} \frac{d\hat{\sigma}}{d\hat{t}}[ab \rightarrow C\bar{C}({}^{2S+1}L_J^{(8)})c \\ \rightarrow \psi_Q(\chi_J)], \end{aligned} \quad (6)$$

where the partonic level differential cross section is given by

$$\begin{aligned} \frac{d\hat{\sigma}}{d\hat{t}}[ab \rightarrow C\bar{C}({}^{2S+1}L_J^{(8)})c \rightarrow \psi_Q(\chi_J)] \\ = \frac{1}{16\pi\hat{s}^2} \Sigma |\mathcal{A}[ab \\ \rightarrow C\bar{C}({}^{2S+1}L_J^{(8)})c]|^2 \langle 0 | \mathcal{O}_8^{\psi_Q(\chi_J)} ({}^{2S+1}L_J) | 0 \rangle. \end{aligned} \quad (7)$$

In our calculation, all the partonic level matrix elements squared

$$\Sigma |\mathcal{A}[ab \rightarrow C\bar{C}({}^{2S+1}L_J^{(8)})c]|^2$$

and the nonperturbative matrix elements

$$\langle 0 | \mathcal{O}_8^{\psi_Q(\chi_J)} ({}^{2S+1}L_J) | 0 \rangle$$

are taken from [5].

For the rapidity distribution and total cross section of  $J/\psi$  production, the leading contribution is proportional to  $\alpha_s^2$  and we will only consider that contribution here. In leading order, the parton fusion processes contribute to the total cross section for  $J/\psi$  ( $\chi_J$ ) production in  $pp$  collisions as follows:

$$\begin{aligned} \sigma^{pp \rightarrow J/\psi(\chi_J)} = \sum_{a,b} \int dx_a \int dx_b f_{a/A}(x_a, Q^2) \\ \times f_{b/B}(x_b, Q^2) \sigma^{ab \rightarrow J/\psi(\chi_J)}(\hat{s}) \delta(x_a x_b \\ - 4m^2/s), \end{aligned} \quad (8)$$

where  $\sigma^{ab \rightarrow J/\psi(\chi_J)}(\hat{s})$  is the partonic level cross section at leading order which are derived in [5,11]. In the above equation,  $m$  is the mass of the charm quark. At the leading order, not all the processes contribute to the total cross section in the singlet and octet channel. In the color singlet channel, the  $J/\psi$  production cross section at  $\alpha_s^2$  order is given by:

$$\sigma_1^{pp \rightarrow J/\psi}(s) = \sigma_1^{pp \rightarrow \chi_0}(s) BR_{\chi_0}, \quad + \sigma_1^{pp \rightarrow \chi_2}(s) BR_{\chi_2}. \quad (9)$$

Here,  $BR_\chi$  refers to the branching ratio of a  $\chi$  to decay into a  $J/\psi$ . Similarly in the octet channel at the leading order, the  $J/\psi$  production cross section is given by:

$$\begin{aligned} \sigma_8^{pp \rightarrow J/\psi}(s) = \sigma_8^{pp \rightarrow J/\psi}(s) + \sigma_8^{pp \rightarrow \chi_1}(s) BR_{\chi_1} \\ + \sigma_8^{pp \rightarrow \chi_0}(s) BR_{\chi_0} + \sigma_8^{pp \rightarrow \chi_2}(s) BR_{\chi_2}. \end{aligned} \quad (10)$$

In the above equations, the direct  $J/\psi$  production and the decay of  $\chi_c$  with their corresponding branching ratios to  $J/\psi$  are included. In the leading order, we use the same values of the nonperturbative matrix elements used in the singlet and octet channels as in [12].

We will use the Glück-Reya-Vogt 1998 (GRV98) [13] and Martin-Roberts-Stirling-Thorne 1999 (MRST99) [14] parton distribution functions inside the proton. The factorization scales are set to be  $Q = 2m$  for the total cross section and rapidity distribution plots, and  $Q = \sqrt{p_T^2 + M^2}$  for the plot of the  $p_T$  distribution.

In Fig. 1 we present the  $p_T$  distribution of the  $J/\psi$  production cross section separately for the color singlet and color octet mechanism including the effects of cuts due to the PHENIX detector acceptance range. We have considered all the parton fusion processes [5,15] in our calculation. In these plots we have used the GRV98 and MRST99 parton distribution functions. As the nonperturbative NRQCD matrix elements has uncertainties as given in [5], we present two plots for each of the PDF's which correspond to the upper and lower limit on the nonperturbative matrix elements. The solid line corresponds to the results obtained by using the GRV98 PDF's with lowest values of the nonperturbative matrix elements as given in [5]. The upper dashed line corresponds to the results obtained by using the GRV98 PDF's with highest values of the nonperturbative matrix elements. The upper dotted-dashed line corresponds to the

results obtained by using the MRST99 PDF's with highest values of the nonperturbative matrix elements. The lower dotted-dashed line corresponds to the results obtained by using the MRST99 PDF's with lowest values of the nonperturbative matrix elements. The lower dashed line corresponds to the color singlet contribution. We have compared our calculation with the recent PHENIX data (run3). The daggers are recent PHENIX data taken from [8]. It can be seen from the figure that the color singlet contribution is more than an order of magnitude smaller than the octet contribution. On the other hand, the color octet mechanism with only parton fusion processes reproduces the recent PHENIX data very well. Thus for  $p_T \leq 5$  GeV, we do not find it necessary to include contributions from the parton fragmentation processes. We have not compared our calculation with the data below  $p_T$  equal to 2 GeV, as pQCD calculations are not valid at such low transverse momenta. In the near future, PHENIX will have sensitivity up to  $p_T = 10$  GeV. This new data will tell us whether it is necessary to include contributions from fragmentation processes to interpret the high  $p_T$  data.

In Fig. 2 we present the rapidity distribution of the  $J/\psi$  production cross section in  $pp$  collisions at RHIC at  $\sqrt{s} = 200$  GeV. We have taken the charm quark mass equal to 1.45 GeV in our calculation. The solid line is the results obtained by using the GRV98 PDF's with lowest values of the nonperturbative matrix elements. The upper dashed line corresponds to the results obtained by using the

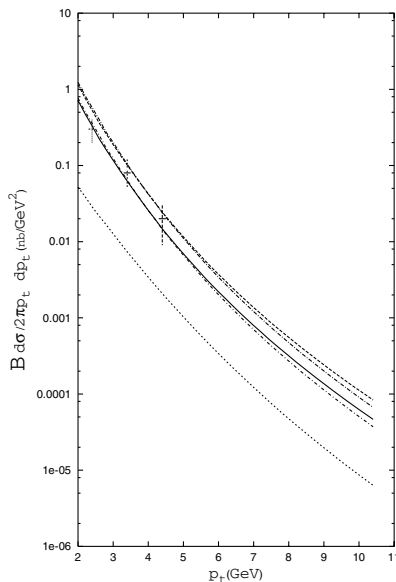


FIG. 1.  $p_T$  distribution of  $J/\psi$  production cross section in  $pp$  collisions at  $\sqrt{s} = 200$  GeV at RHIC in the PHENIX detector acceptance range. The solid and upper dashed lines and upper/lower dotted-dashed lines correspond to color octet mechanism predictions with GRV98 and MRST99 PDF's. The lower dashed line is the color singlet contribution. The daggers are run3 PHENIX experimental data.

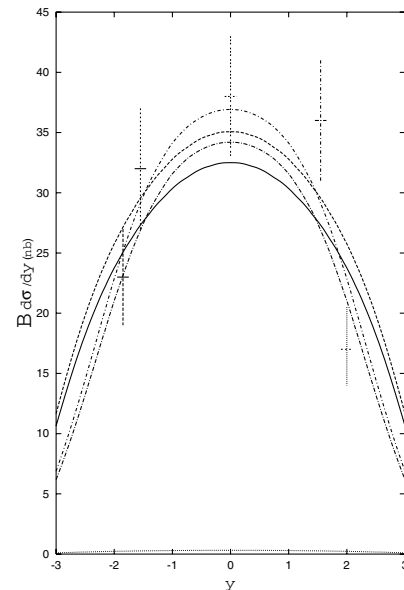


FIG. 2. Rapidity distribution of  $J/\psi$  production cross section in  $pp$  collisions at  $\sqrt{s} = 200$  GeV at RHIC in the PHENIX detector acceptance range. The solid and upper dashed lines and upper/lower dotted-dashed lines correspond to color octet mechanism predictions with GRV98 and MRST99 PDF's. The lower dashed line is the color singlet contribution. The daggers are run3 PHENIX experimental data.

GRV98 PDF's with highest values of the nonperturbative matrix elements. The upper dotted-dashed line corresponds to the results obtained by using the MRST99 PDF's with highest values of the nonperturbative matrix elements. The lower dotted-dashed line corresponds to the results obtained by using the MRST99 PDF's with lowest values of the nonperturbative matrix elements. The PHENIX experimental data [8] are shown in the figure as daggers. The rapidity range covered by PHENIX at RHIC is from  $-3 < y < 3$ . The color singlet contribution is also shown as the lower dashed line (here we only show the results using the GRV98 PDF's) which is very small when compared with the color octet contribution. It can be seen that just including the color octet contribution explains the run3 PHENIX data.

The total cross section ( $B\sigma_{J/\psi}$ ) found by run3 PHENIX experiment at  $\sqrt{s} = 200$  GeV was reported to be 159 (nb) [8]. The color octet contribution we find to be  $159 \pm 6$ . The  $\pm 6$  (nb) is due to the errors in the nonperturbative matrix elements as given in [5]. In the above total cross section computation, we have used charm quark mass equal to 1.45 GeV and the MRST99 parton distribution function inside the proton. The agreement of color octet mechanism predictions with the PHENIX experimental data is remarkable in all aspects, *i.e.*, in  $p_T$  distribution, in rapidity distribution, and in total cross section measurements at  $\sqrt{s} = 200$  GeV  $pp$  collisions.

Before summarizing, we briefly discuss the uncertainties due to PDF's, nonperturbative matrix elements, etc. As can be seen from Figs. 1 and 2, both GRV98 and MRST99 PDF's describe the data very well. We have also checked that the recent CTEQ6M PDF's also explain the data very well. The uncertainty in the results due to the errors in the nonperturbative matrix elements are given in Figs. 1 and 2 and also in the total cross section.

In summary, in this Letter, we have studied  $J/\psi$  production in  $pp$  collisions at RHIC at  $\sqrt{s} = 200$  GeV within the PHENIX detector acceptance range by using the color singlet and the color octet mechanism within pQCD and NRQCD and have compared them with the recent PHENIX experimental data. We have demonstrated that the color octet mechanism using only parton fusion processes is able to reproduce the RHIC data on the  $p_T$  distribution, rapidity distribution, and total cross section of  $J/\psi$  production. This is done without any normalization factor modifications and using matrix elements extracted from the Tevatron and other experiments. The color singlet mechanism gives negligible contributions when compared to the octet contributions at this energy. Our results confirm the applicability of the color octet mechanism found at the Tevatron.

It is important to identify the correct mechanism for  $J/\psi$  production in  $pp$  collisions at RHIC if we want to study  $J/\psi$  suppression as a signature of quark-gluon plasma detection in Au-Au collisions at  $\sqrt{s} = 200$  GeV [7].

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