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Heavy-Quarkonium Production in High Energy Proton-Proton Collisions at RHIC

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We update the study of the total ψ and Υ production cross section in proton-proton collisions at RHIC energies using the QCD-based Color-Singlet (CS) Model, including next-to-leading order partonic matrix elements. We also include charm-quark initiated processes which appear at leading order in α_s, but which have so far been overlooked in such studies. Contrary to earlier claims, we show that the CS yield is consistent with measurements over a broad range of J/ψ rapidities. We also find that charm-quark initiated processes, including both intrinsic and sea-like charm components, typically contribute at least 20 % of the direct J/ψ yield, improving the agreement with data both for the integrated cross section and its rapidity dependence. The key signature for such processes is the observation of a charm-quark jet opposite in azimuthal angle ϕ to the detected J/ψ. Our results have impact on the proper interpretation of heavy-quarkonium production in heavy-ion collisions and its use as a probe for the quark-gluon plasma.

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The hadroproduction of heavy-quarkonium states such as the J/ψ and Υ is one of the key topics in phenomenological QCD. As opposed to lighter mesons, it is a priori straightforward to compute their production rates from gluon-induced subprocesses such as $gg \to \mathcal{Q}g$ (Fig. 1 (a)), particularly since one can use a nonrelativistic approximation for the quarkonium wavefunction. However, there are many outstanding theoretical issues, including the role of color-octet (CO) intermediate $[Q\bar{Q}]_{8C}$ configurations, the impact of next-to-leading order (NLO) – and even higher order – QCD corrections (Fig. 1 (c,d)), and the role of hard subprocesses such as $gc \to J/\psi c$ (Fig. 1 (b)) which utilize the charm-quark distribution in the target or projectile, whether generated by intrinsic heavy-quark mechanisms, or simply by Q^2 evolution. Other empirical issues include the J/ψ polarization puzzle, the factorization-breaking strong nuclear dependence measured in J/ψ hadroproduction at high x_F, and the uncertain effects of rescattering and energy loss mechanisms. All of these issues have impact on the proper interpretation of heavy-quarkonium production in heavy-ion collisions and its use as a probe for the quark-gluon plasma. For recent reviews, see [1].

It is widely accepted that α_s^4 and α_s^5 corrections are fundamental for understanding the p_T spectrum of J/ψ and Υ produced in high-energy hadron collisions [1]. However, if anomalously large contributions to the total cross section arise from NLO contributions, this would cast doubt on the convergence of the expansion in α_s. It is thus important to check that LO and NLO predictions are close to each other and in agreement with experimental data. In this paper we carry out the first theoretical analysis at NLO accuracy of the total J/ψ, $\psi(2S)$, and Υ production in pp collisions at the BNL RHIC. We show that hard subprocesses based on CS $Q\bar{Q}$ configurations alone are sufficient to account for the observed magnitude of the p_T-integrated cross section. In particular, the predictions at LO [2] and NLO [3, 4] accuracy are both compatible with measurements by the PHENIX collaboration at RHIC [5] within present errors. We shall also show that hard subprocesses involving the charm quark distribution of the colliding protons (Fig. 1 (b)) which constitute part of the

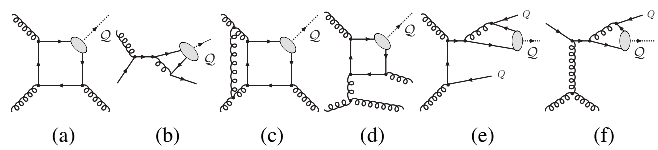

FIG. 1: Representative diagrams contributing to ${}^3S_1$ hadroproduction via CS channels at orders α_S^3 (a,b), α_S^4 (c,d,e,f). The quark and antiquark attached to the ellipsis are taken as on-shell and their relative velocity v is set to zero.

LO (α_s^3) rate, are responsible for a significant fraction of the observed yield. It is important to note that reactions such as $gc \to J/\psi c$ (thereafter referred to as cg fusion) also produce a charm jet opposite in azimuthal angle to the J/ψ; furthermore, the rapidity dependence of this "away-side" correlation is strongly sensitive to the mechanism for the creation of the c-quark in the proton.

Subprocesses involving cg fusion with a charm quark from the proton have been considered so far in the literature with a main focus on the high p_T spectrum of heavy quarkonium [6, 7]. We note that at low transverse momentum, the typical scale of the production process is rather small, and thus one does not expect higher-order QCD corrections such as gluon splitting into $c\bar{c}$ to give a significant contribution to the total cross section for quarkonium hadroproduction. For example, the contribution to the total cross section from the process $gg \to J/\psi c\bar{c}$, appearing at α_s^4 (Fig. 1 (e)) [9], contributes at the level of 0.5 %. In contrast, in the case of intrinsic charm (IC) contributions, the c and $\bar{c}$ quarks are created from two soft gluons connecting to different valence quarks in the proton as in the BHPS model [8]; such contributions are relevant to charmonium production at all scales.

We shall focus here on the "direct" hadroproduction of the J/ψ, $\psi(2S)$, and $\Upsilon(1S)$ without the contribution arising from the decay of heavier states; this avoids the discussion of the production mechanisms of P-waves which are not well understood. Although the total cross section for $L = 1$ states has been studied at NLO [10], an effective evaluation of the

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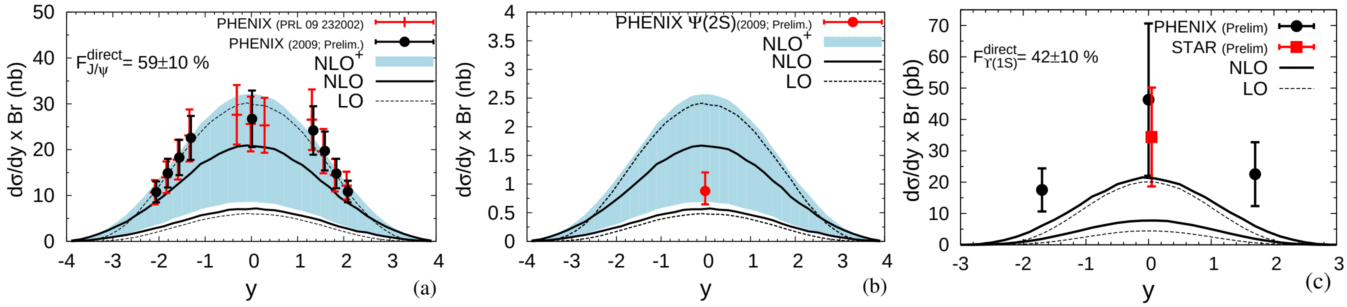

FIG. 2: (a) $d\sigma^{direct}_{J/\psi}/dy \times$ Br extrapolated from the measurements by PHENIX [5, 17] compared to the CSM at LO (α_s^3) by gg fusion only (thin-dashed lines), at NLO (up to α_s^4) by gg and qg fusion only (thick-solid lines) and the sum "NLO + cg fusion", denoted NLO$^+$ (light-blue band). (b) same as (a) for the $\psi(2S)$ with PHENIX data [17]. (c) same as (a) for the direct Υ with extrapolated STAR [20] and PHENIX [17, 21] preliminary measurements (without NLO$^+$, see text).

production cross section requires the introduction of an infrared cut-off (as for their decay [11]) or CO contributions [12] which introduce new unknown non-perturbative parameters. Furthermore, the impact of the off-shellness of initial gluon on the χ_{c1} yield may be significant [13, 14]. We have also restricted our analysis to the integrated-p_T distribution. Indeed, as noticed at the Tevatron energy [3, 4], the NLO p_T distribution, contrary to the integrated one, can be negative at low p_T. While it is not the case here, initial-state radiation [15] is still expected to modify significantly the spectrum at low p_T.

In the case of J/ψ hadroproduction, the PHENIX data [5] includes the direct yield, in which we are interested, but also a B feed-down fraction estimated to be $4^{+3}_{-2}\%$ [16], feed-down from $\psi(2S)$ decay which is measured [17] to be $8.6 \pm 2.5\%$ for $|y| < 0.35$ and the feed-down from χ_c decay which has been estimated $< 42\%$ at 90% C.L. [16]. A recent analysis [18] from fixed-target measurements in pA suggests that it amounts to $25 \pm 5\%$, while the CDF measurement in pp at Fermilab gives $30 \pm 6\%$ of the *prompt* yield for $p_T > 4$ GeV [19]. For our analysis, we will make the hypothesis that the χ_c feed-down fraction is $30 \pm 10\%$ of the prompt yield independent of rapidity. Overall, we shall take $F^{\rm direct}_{J/\psi} = 59 \pm 10\%$.

As regards J/ψ production, the differential cross section as function of y has been measured by PHENIX in the central ($|y| < 0.35$) as well as in the forward ($1.2 < |y| < 2.2$) regions [5, 17]. The extrapolation to the direct yield using $F^{\rm direct}_{J/\psi} = 59 \pm 10\%$ is shown on Fig. 2 (a). For the $\psi(2S)$, only a negligible B feed-down competes with the direct mechanism. The preliminary measurement by PHENIX is shown on Fig. 2 (b). The $\Upsilon(nS)$ cross section in pp collisions has been measured by STAR [20] and PHENIX [17] in the central region, and by PHENIX [21] in the forward regions. From the CDF analysis [22] at $p_T > 8$ GeV, 50% of the $\Upsilon(1S)$ are expected to be direct. Using the relative yields from [23], we expect $42 \pm 10\%$ of the $\Upsilon(nS)$ signal to be direct $\Upsilon(1S)$. The result of PHENIX and STAR combined with this fraction are displayed on Fig. 2 (c).

In our evaluation, we use the partonic matrix elements from Campbell, Maltoni and Tramontano [3] to compute the LO and NLO cross sections from gluon-gluon and light-quark gluon fusion. In the case of the cg fusion, we use the framework described in [25] based on the tree-level matrix element generator MadOnia. For the parameters entering the cross section evaluation, we have taken $|R_{J/\psi}(0)|^2 = 1.01$ GeV^3 and $|R_{\psi(2S)}(0)|^2 = 0.639$ GeV^3 determined from their leptonic decay [27]. We also take Br$(J/\psi \to \ell^+\ell^-) = 0.0594$ and Br$(\psi(2S) \to \ell^+\ell^-) = 0.0075$. For the $\Upsilon(1S)$, we will choose $|R(0)|^2 = 7.6$ GeV^3, and Br$(\Upsilon \to \ell^+\ell^-) = 0.0218$. The uncertainty bands for the resulting predictions are obtained from the combined variations of the heavy-quark mass within the ranges $m_c = 1.5 \pm 0.1$ GeV and $m_b = 4.75 \pm 0.25$ GeV, as well as the factorization μ_F and the renormalization μ_R scales [28] chosen in the couples $((0.75, 0.75); (1, 1); (1, 2); (2, 1); (2, 2)) \times m_T$ with $m_T^2 = 4m_Q^2 + p_T^2$. Neglecting relativistic corrections, one has in the CSM, $M_{J/\psi} = M_{\psi(2S)} = 2m_c$ and $M_\Upsilon = 2m_b$. The parton distribution set used was CTEQ6_L [29] for the LO gg fusion, CTEQ6_M for the $gg + gq$ NLO one and, for the cg fusion, CTEQ6.5c [30] based on a recent global PDF fit including IC. We have employed three choices for the charm distribution: (i) without IC, (ii) with BHPS IC [8] ($\langle x \rangle_{c+\bar{c}} = 2\%$) and (iii) with sea-like IC ($\langle x \rangle_{c+\bar{c}} = 2.4\%$) . While there does exist an intrinsic b-quark content in the proton scaled by m_c^2/m_b^2 relative to IC, its corresponding contribution to $\Upsilon + b$ is additionally suppressed at RHIC energy by phase space due to the presence of an additional b-quark in the final state.

We now describe our results. As shown in Fig. 2 (a) and (b), the LO and NLO yields are consistent in size, and the uncertainty of the NLO contribution (indicated by the two curves in both cases) is smaller than that of the LO. This provides some indication that we are in a proper perturbative regime. The contributions at LO and NLO accuracy are compatible with the experimental data from PHENIX, in contrast to the conclusion of [31], in which feed-down from P-waves was incorrectly assumed to be the dominant source of J/ψ production. This supports the good description of STAR results [33] for the J/ψ differential cross section at mid p_T predicted by the CSM at NLO including leading-p_T α_s^5 contributions (NNLO*)[34]. Note that a significantly larger CS yield points to a small impact from s-channel cut contributions [32]. Even though the NLO is close to the data, the additional cg

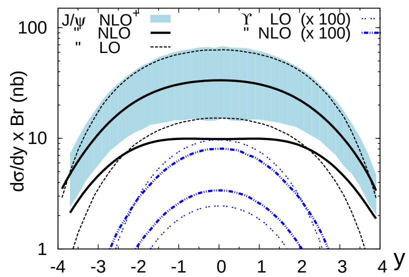

FIG. 3: $d\sigma/dy \times Br$ for the direct yield of J/ψ and Υ as a function of y at $\sqrt{s}$ = 500 GeV for the same parameter ranges as Figs. 1.

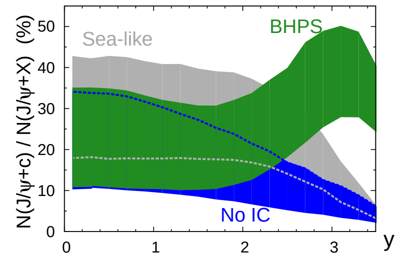

FIG. 4: Fraction of J/ψ produced in association with a single c-quark relative to the direct yield (NLO$^+$) as a function of y_ψ and for three models for $c(x)$.

contribution (even with a sea-like IC distribution) improves the agreement. However, it should be noted that phase space effects are not properly taken into account in the case of $\psi(2S)$ production due to the restriction $M_{\psi(2S)} = 2m_c$. The comparison with the measurement of $\psi(2S)$ hadroproduction is nevertheless encouraging, particularly since unlike J/ψ production, it does not involve the uncertainties arising from the extrapolation of the experimental data to the direct yield. We also give in Fig. 3 our prediction at $\sqrt{s}$ = 500 GeV for the direct J/ψ and Υ yield for future comparison with the data taken this year.

We note that the contribution from cg fusion is significant for both J/ψ and $\psi(2S)$ production and calls for a deeper analysis. The results labeled NLO$^+$ were obtained with the sea-like IC from CTEQ 6.5c. To precisely assess the impact of other choices for the charm distribution, $c(x)$, we have evaluated the fraction of J/ψ produced in association with a single c-quark relative to the direct yield as a function of y_ψ and for the three models for $c(x)$. Those are displayed on Fig. 4 for which we have set m_c = 1.4 GeV and varied μ_F and μ_R within the same values as for Figs. 2. This clearly confirms the impact of the cg contribution, which ranges from 10 % up to 45% of the direct yield in the case of sea-like $c(x)$. Note also that at larger p_T, we expect significant α_s^4 contributions from cg fusion, since they then exhibit a fragmentation-like topology (Fig. 1 (f)). This was studied by Qiao [7] for the Tevatron using a conventional c-quark distribution, but this evaluation cannot be extended to small p_T where it is infrared divergent. In the case of the BHPS IC distribution, the p_T distribution at large p_T and RHIC energy will show an analogous enhancement as seen at large rapidity in Fig. 4. This may also impact the J/ψ yield in this region [35]. In order to assess experimentally the importance of cg fusion, a measurement of J/ψ in association with D meson would be ideal, along the same line as [9] for $J/\psi + c\bar{c}$. More accessible is the study of the azimuthal correlation of $J/\psi + e$ in the central region by PHENIX and STAR and of $J/\psi + \mu$ in the forward region by PHENIX. The key signature for such subprocesses is the observation a lepton excess opposite in azimuthal angle ϕ to the detected J/ψ. Finally, this study, like the study of $J/\psi + \gamma$ [36, 37], has the further merit of being univocally sensitive to the CS yield. In particular, it should be emphasized that color transfers [38] will not occur since the three heavy quarks are well separated, the third quark recoiling on the J/ψ (Fig. 1 (b)).

In addition to the $gc \to J/\psi c$ subprocesses, one can also have, at large rapidity, $(c\bar{c})g \to J/\psi$ contributions to the total cross section [40, 41] from the coalescence of the charm pair and gluon; in this case the J/ψ acquires the momentum of both the c and $\bar{c}$ quarks from the projectile or target wavefunction. In particular, the $c\bar{c}$ contributions from CO+CO intrinsic charm Fock states such as $|(c\bar{c})_{8_C}(uud)_{8_C}\rangle$ can explain J/ψ and double J/ψ production at high $x_F > 0.6$ observed in pA and πA collisions by the CERN NA3 experiment as well as the anomalous nuclear dependence [24].

We now turn to Υ hadroproduction; in this case, the bg fusion processes are suppressed by phase-space and the $1/m_b^2$ dependence of the b-quark content in the proton. Thus we have only computed the LO and NLO yield from gg and qg (see Fig. 2 (c)). The predictions are not far from the extrapolation of preliminary data by PHENIX and STAR. In addition, the consistency between CDF data at the Tevatron at mid and large p_T and the very first NNLO* CS analysis [34] also suggests that Υ production can be understood from perturbative QCD. We also emphasize here that the rapidity region accessible at RHIC allows for measurements of Υ production at high x_F very close to 1. In such a case, the intrinsic bottom quark pair can simply coalesce to form a Υ after a single scattering to change its color in $(b\bar{b})_{8_C} + g \to \Upsilon$ in analogy to the large x_F J/ψ production [41]. It does not require a third b-quark and is thus not suppressed by phase-space effects. One can possibly attribute the excess visible at $|y| \simeq 2$ in the PHENIX measurements to this mechanism. The $(Q\bar{Q})g$ subprocesses also have implications for Higgs hadroproduction at high x_F [26].

We now briefly discuss the production of J/ψ in pA collisions as CS states, which we claim here to be the dominant mechanism at RHIC energy. In the central rapidity region, the $c\bar{c}$ pair will become the physical hadron outside the nucleus. Although the energy loss of a colored object in cold nuclear matter is limited to be constant, rather than scaling with energy, by the Landau- Pomeranchuk-Migdal effect [43], the magnitude of energy loss per unit of length will be significantly larger for a CO than for a CS state. The recent observation by STAR [33] of the non-suppression of J/ψ in Cu-Cu collisions at increasing p_T clearly supports the hypothesis that the J/ψ is produced by a hard subprocess where the $c\bar{c}$ is in a colorless state. The dominant hard QCD subprocess for J/ψ hadroproduction is thus a $2 \to 2$ reaction in contrast to the feed-down $gg \to \chi_{c2} \to J/\psi\gamma$ or CO mechansim such as $gg \to (c\bar{c})_{8C} \to J/\psi g$ [31]. The correct implementation of the nuclear shadowing should be done along the lines of [42], both for gg and cg part, although the shadowing of c-quark distributions is poorly known. Thus the dedicated study of $J/\psi + c$ in pA collisions could provide a unique way to study such shadowing effects as well as heavy-quark energy loss. We also note that the yield from cg subprocesses is expected to have the usual factorizing nuclear dependence $A^{\alpha(x_2)}$, where x_2 is the light-front momentum fraction of the nuclear parton, in contrast to the factorization breaking behavior $A^{\alpha(x_F)} \sim A^{2/3}$ observed at high x_F [24, 39]. This anomalous nuclear dependence can however be understood from large-x_F production due to the coalescence of IC pairs turning into CS pairs after interacting with partons from the target surface [26, 40, 41].

In conclusion, we have carried out the first theoretical analysis at NLO accuracy of J/ψ, $\psi(2S)$ and Υ production at RHIC and have shown that the CS yield is in good agreement with all the experimental data from the PHENIX and STAR collaborations. We have also shown that c-quark–gluon fusion is responsible for a significant, and measurable, part of the yield, and we call for a dedicated measurement to pin down this contribution and assess the importance of the charm content of the proton. We predict a significant excess of the lepton yield on the "away" side of the J/ψ arising from c-quark jet and argue that the rapidity dependence of this correlation is strongly sensitive on the specific mechanisms for the creation of charm in the proton. Finally, we have discussed the implication of our work on heavy-ion studies.

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