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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 model, including next-to-leading order partonic matrix elements. We also include charm-quark initiated processes which appear at leading order in α_s, so far overlooked in such studies. Contrary to earlier claims, we show that the color-singlet yield is consistent with measurements over a broad range of J/ψ rapidities. We find that intrinsic plus sealike charm-initiated processes contribute more than 20% of the direct J/ψ yield. 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 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 nonrelativistic approximations. However, there are many outstanding theoretical issues, including the role of color-octet (CO) states, the impact of next-to-leading order (NLO)—and even higher-order QCD corrections (Fig. 1(a) and 1(d)), and the role of hard subprocesses such as $gc \to J/\psi c$ (Fig. 1(b)) which utilize the c-quark distribution in the proton. Other issues include the J/ψ polarization puzzle, the factorization-breaking strong nuclear dependence 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 to the color-singlet model (CSM) [2] are fundamental for understanding the p_T spectrum of J/ψ and Υ produced in high-energy hadron collisions [3–8]. However, if anomalously large contributions to the total cross section arise from α_S^4 graphs, 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 in the CSM 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 color-singlet $Q\bar{Q}$ 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 [9] 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 LO (α_s^3) rate, are responsible for a significant fraction of the observed yield. Reactions such as $gc \to J/\psi c$ (hereafter 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. An analysis of the invariant mass distribution of the $J/\psi + D$ pair may also shed light on possible contributions beyond the color-singlet model, as described by the color-transfer mechanism (CTM) [10,11].

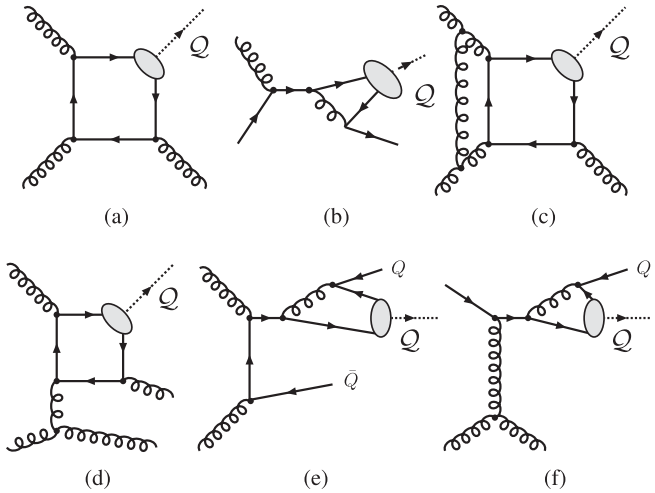

FIG. 1. Representative diagrams contributing to $^3S_1$ quarkonium (denoted $\mathcal{Q}$) hadroproduction via CS channels at orders α_S^3 (a, b), α_S^4 (c, d, e, f). The quark and antiquark attached to the ellipsis are taken as on-shell and their relative velocity v is set to zero.

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Subprocesses involving cg fusion with a charm quark from the proton have been considered in [12,13] with the main focus on the high p_T spectrum. At low p_T, 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 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)) [14], is 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 Brodsky-Hoyer-Peterson-Sakai (BHPS) model [15]; such contributions are relevant to charmonium production at all scales. The contribution from $c\gamma$ fusion was studied in photoproduction in [16].

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 [17], an effective evaluation of the production cross section requires the introduction of an infrared cutoff (as for their decay [18]) or CO contributions [19] which introduce new unknown nonperturbative parameters. Furthermore, the impact of the off-shellness of initial gluon on the χ_{c1} yield may be significant [20,21]. 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. In addition, initial-state radiation [22] would also be expected to significantly modify the spectrum at small p_T and to increase $\langle p_T^2 \rangle$.

In the case of J/ψ hadroproduction, the PHENIX data [9] includes the direct yield, but also a B feed-down fraction (4^{+3}_{-2}% [23]), a $\psi(2S)$ feed-down (8.6 ± 2.5% for $|y| < 0.35$), and a χ_c feed-down estimated to be <42% at 90% C.L. [23]. A recent analysis [24] from fixed-target measurements in pA suggests that it amounts to 25 ± 5%, while the CDF measurement in pp at Fermilab gives 30 ± 6% of the *prompt* yield for $p_T > 4$ GeV [25]. For our analysis, we will make the hypothesis that the χ_c feed-down fraction is 30 ± 10% of the prompt yield independent of rapidity. Overall, we shall take $F^{\text{direct}}_{J/\psi} = 59 \pm 10\%$ and multiply the PHENIX results by this factor. The differential J/ψ production cross section vs y has been measured by PHENIX in the central ($|y| < 0.35$) as well as in the forward ($1.2 < |y| < 2.2$) regions [9,26]. The extrapolation to the direct yield using $F^{\text{direct}}_{J/\psi} = 59 \pm 10\%$ 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 $\Upsilon(1S + 2S + 3S)$ cross section has been measured by STAR [27] and PHENIX [26] in the central region, and by PHENIX [28] in the forward regions. From the CDF analysis [29] at $p_T > 8$ GeV, 50% of the $\Upsilon(1S)$ are expected to be direct. Using the relative yields from [30], we expect 42 ± 10% of the $\Upsilon(1S + 2S + 3S)$ signal to be direct $\Upsilon(1S)$. PHENIX and STAR data multiplied by this fraction are displayed on Fig. 2(c).

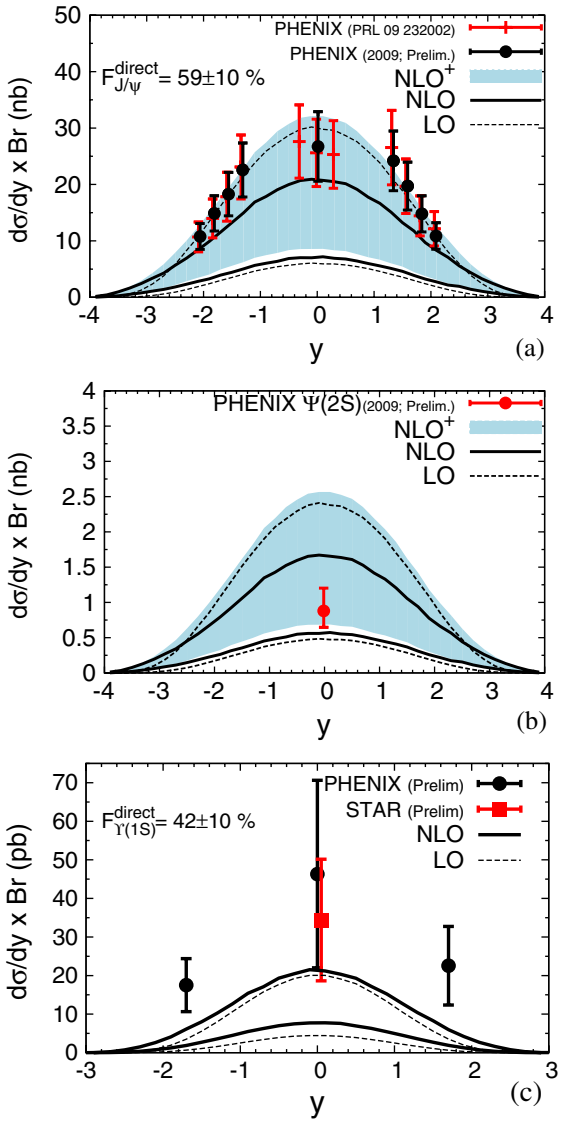

FIG. 2 (color online). (a) $d\sigma^{\text{direct}}_{J/\psi}/dy \times \text{Br}$ from the measurements by PHENIX [9,26] multiplied by our estimate of $F^{\text{direct}}_{J/\psi}$ compared to the CSM at LO (α_s^3) by gg fusion only (thin dashed lines), at NLO (up to α_s^4) by gg and qg fusion only (thick solid lines) and the sum "NLO + cg fusion" with the sealike $c(x)$ [38], denoted NLO$^+$ (light-blue band). (b) same as (a) for the $\psi(2S)$ with PHENIX data [26]. (c) same as (a) for the direct Υ with STAR [27] and PHENIX [26,28] preliminary measurements for $\Upsilon(1S + 2S + 3S)$ multiplied by our estimate of $F^{\text{direct}}_{\Upsilon}$ (without NLO$^+$; see text). The gaps between the two solid and the two dashed lines as well as the band reflect the variation of the cross section after a *combined* variation of the scales and the masses as indicated in the text.

In the CSM [2], the matrix element to create a $3S_1$ quarkonium $\mathcal{Q}$ of momentum P and polarization λ accompanied by other partons, noted j, is the product of the

amplitude to create the corresponding heavy-quark pair, a spin projector $N(\lambda|s_1, s_2)$, and $R(0)$, the radial wave function at the origin in the configuration space, obtained from the leptonic width [31], namely

$$\mathcal{M}(ab \to \mathcal{Q}^\lambda(P) + j) = \sum_{s_1,s_2,i,i'} \frac{N(\lambda|s_1, s_2)}{\sqrt{m_Q}} \frac{\delta^{ii'}}{\sqrt{N_c}} \frac{R(0)}{\sqrt{4\pi}} \times \mathcal{M}(ab \to Q_i^{s_1} \bar{Q}_{i'}^{s_2}(\mathbf{p} = \mathbf{0}) + j), \quad (1)$$

where $P = p_Q + p_{\bar{Q}}$, $p = (p_Q - p_{\bar{Q}})/2$, s_1, s_2 are the heavy-quark spin, and $\delta^{ii'}/\sqrt{N_c}$ is the projector onto a CS state. In the nonrelativistic limit, $N(\lambda|s_1, s_2)$ can be written as $\frac{\varepsilon_\mu^\lambda}{2\sqrt{2}m_Q} \bar{v}(\frac{\mathbf{P}}{2}, s_2)\gamma^\mu u(\frac{\mathbf{P}}{2}, s_1)$ where ε_μ^λ is the polarization vector of the quarkonium. The sum over the spins yields to traces evaluated in a standard way.

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. We guide the reader to [3] for details concerning the derivation of $\mathcal{M}(ab \to \mathcal{Q}^\lambda(P) + j)$ at α_s^4; the corresponding expressions at α_s^3 can be found in [32]. In the case of the cg fusion (at LO), we use the framework described in [33] based on the tree-level matrix element generator MADONIA [34]. 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. We also take $\mathrm{Br}(J/\psi \to \ell^+\ell^-) = 0.0594$ and $\mathrm{Br}(\psi(2S) \to \ell^+\ell^-) = 0.0075$. For the $\Upsilon(1S)$, we will choose $|R(0)|^2 = 7.6$ GeV^3 and $\mathrm{Br}(\Upsilon \to \ell^+\ell^-) = 0.0218$. 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,[1] the factorization μ_F, and the renormalization μ_R scales chosen[2] 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 used was the LO set CTEQ6_L [37] for the LO gg fusion, the NLO set CTEQ6_M for the $gg + gq$ NLO one, and for the cg fusion the LO set CTEQ6.5c [38] based on a recent global parton distribution function fit including IC. We have employed three choices for the charm distribution: (i) without IC $[c(x, \mu_0) = 0$ ($\mu_0 = 1.2$ GeV)], (ii) with BHPS IC [15] ($\langle x \rangle_{c+\bar{c}} \equiv \int_0^1 x[c(x) + \bar{c}(x)]dx = 2\%$), and (iii) with sealike IC ($\langle x \rangle_{c+\bar{c}} = 2.4\%$).

[1]It is common to see a wider range used for m_c in NLO evaluations of open-charm cross sections, i.e. $m_c = 1.5 \pm 0.2$ GeV (see [35]). In the case of quarkonium production within the CSM, such values so different from $M_Q/2$ may require the inclusion of nonstatic corrections, which is beyond the scope of our analysis. See also our comment regarding the $\psi(2S)$ results.

[2]In principle, the renormalization scale ambiguity can be removed using the method described in [36].

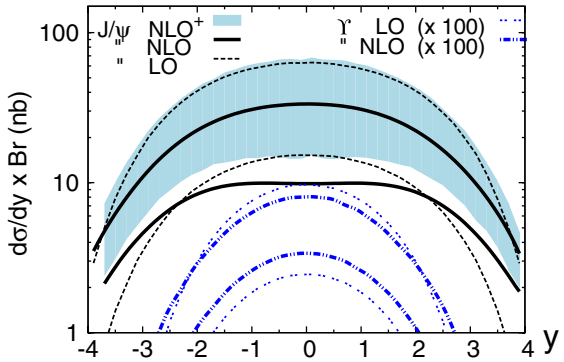

FIG. 3 (color online). $d\sigma/dy \times \mathrm{Br}$ for the direct yield of J/ψ and Υ as a function of y at $\sqrt{s} = 500$ GeV for the same parameter ranges as Figs. 1.

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 2(b), the yields at LO and NLO accuracy are consistent in size, and the uncertainty of the latter one (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 yields at LO and NLO accuracy are compatible with the PHENIX data, in contrast to the conclusion of [39], in which feed-down from χ_{c0} and χ_{c2} at α_S^2 was incorrectly assumed to be the dominant source of J/ψ production. This supports the good description of STAR results [40] 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*) [5]. Note that a significantly larger CS yield points to a small impact from s-channel cut contributions [41].

Even though the NLO is close to the data, the additional cg contribution (even with a sealike IC distribution) improves the agreement. However, 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 $\psi(2S)$ case is nevertheless encouraging, since 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 (the results labeled[3] NLO$^+$ were obtained with the sealike IC from CTEQ 6.5c) is significant for both J/ψ and $\psi(2S)$ production and calls for a deeper analysis. First, it should be noted that nonrelativistic QCD factorization-breaking effects, such as those arising from the CTM [10,11] may impact the low p_T region. Such effects arise from infrared-

[3]Notation not to be confused with NLO* or NNLO* which denote real-emission contributions as evaluated in [5].

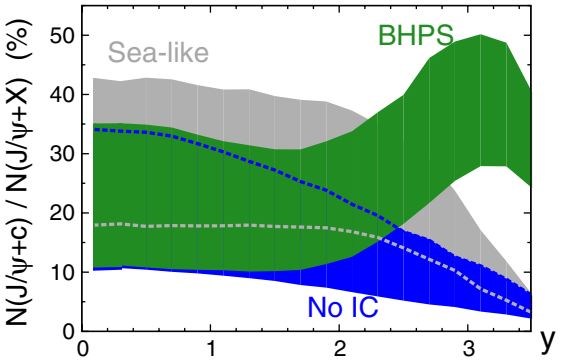

FIG. 4 (color online). Fraction of J/ψ produced in association with a single c-quark (via $gc \to J/\psi c$) relative to the direct yield (NLO$^+$) as a function of y_ψ and for three models for $c(x)$: without IC (No IC), sealike, and BHPS (see text).

sensitive domains at NNLO when the three heavy quarks have comparable velocities. A careful study of the CTM is however beyond the scope of our analysis. Second, 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 $c(x)$. These are displayed on Fig. 4 for which we have set[4] $m_c = 1.4$ 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 sealike $c(x)$.

Note also that at larger p_T, we expect significant α_s^4 contributions from cg fusion, since they then exhibit a fragmentationlike topology (Fig. 1(f)). This was studied by Qiao [13] for the Tevatron using a conventional c-quark distribution, but this evaluation cannot be extended to small p_T where it is infrared divergent. For 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. In order to assess experimentally the importance of cg fusion, whether from the usual CSM or from CTM effects, the measurement of J/ψ in association with D meson would be illuminating, as has been noted in Ref. [14] 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 of a lepton excess opposite in azimuthal angle ϕ to the detected J/ψ.

One can also have, at large rapidity, $(c\bar{c})g \to J/\psi$ contributions to the total cross section [42,43] 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. Intrinsic charm Fock states such as $|(c\bar{c})_{8_C} \times (uud)_{8_C}\rangle$ 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 and its anomalous A dependence [44].

We now turn to Υ hadroproduction where the bg fusion processes are suppressed by phase-space and by 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 [5] 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 where 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 [43]. It does not require a third b-quark and is thus not suppressed by phase-space effects.

We now briefly discuss the production of J/ψ in pA collisions as CS states, likely the dominant mechanism at RHIC energy. In the central region, the $c\bar{c}$ pair hadronizes 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 [45], its magnitude per unit of length will be significantly larger for a CO than for a CS state. The recent observation by STAR [40] 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 mechanism such as $gg \to (c\bar{c})_{8C} \to J/\psi g$ [39]. Nuclear shadowing should then be implemented along the lines of [46], both for gg and cg part, although the c-quark shadowing 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 [44,47], explainable by the coalescence of IC pairs turning into CS pairs after interacting with partons from the target surface [42,43,48].

In conclusion, we have carried out the first NLO analysis in the color-singlet model of J/ψ, $\psi(2S)$, and Υ production at RHIC and have shown that the CS yield is in agreement with the p_T-integrated cross sections measured by the PHENIX and STAR collaborations. We have also shown that c-quark–gluon fusion is responsible for a sig-

[4]Indeed, for our prediction of the ratio to make sense, the color-singlet contribution has to be the dominant one, which can only be the case for a rather low charm-quark mass such as $m_c = 1.4$ GeV.

nificant, 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. Such a study may also shed light on effects due to color-transfer effects beyond the CSM. 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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