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Complete Nonrelativistic-QCD Prediction for Prompt Double J/ψ Hadroproduction

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We perform a complete study of prompt double J/ψ hadroproduction at leading order in the nonrelativistic-QCD factorization framework by including all possible pairings of the $c\bar{c}$ Fock states ${}^1S_0^{[8]}$, ${}^3S_1^{[1,8]}$, and ${}^3P_J^{[1,8]}$ with $J = 0, 1, 2$. We find that the ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ channels of J/ψ and ψ' production and the ${}^3P_J^{[1]}$ and ${}^3S_1^{[8]}$ channels of χ_{cJ} production, which have been overlooked so far, greatly dominate at large invariant masses and rapidity separations of the J/ψ pair, and that their inclusion nearly fills the large gap between previous incomplete predictions within the color-singlet model and the recent measurement by the CMS Collaboration at the CERN LHC, leaving room for next-to-leading-order corrections of typical size.

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The nonrelativistic QCD (NRQCD) [1] factorization formalism, introduced two decades ago in a seminal work by Bodwin, Braaten, and Lepage [2], nowadays is the only game in town for the theoretical description of heavy-quarkonium production and decay, and its experimental verification is generally considered to be among the most urgent tasks of heavy-quarkonium physics [3]. The production cross sections and decay rates are separated into process-dependent short-distance coefficients (SDCs), calculated by expansion in the strong-coupling constant α_s, and universal long-distance matrix elements (LDMEs), which are strongly ordered in size by velocity (v) scaling rules [4]. The heavy-quark pair may appear in any Fock state $n = {}^{2S+1}L_J^{[a]}$, both as color singlet (CS) $a = 1$ and color octet (CO) $a = 8$, thus giving rise to the CO mechanism (COM), while, in the traditional CS model, it is restricted to the CS state sharing the spectroscopic quantum numbers ${}^{2S+1}L_J$ with the physical quarkonium state considered. Despite its aesthetic simplicity and theoretical rigor, consolidated very recently by an all-order proof [5], NRQCD factorization has reached the crossroads because the predicted universality of the LDMEs is challenged [6] by recent measurements of J/ψ polarization [7] and η_c yield [8], which is in the very focus at the CERN LHC.

Our Letter addresses another burning problem of NRQCD, namely, its seeming failure to describe recent measurements of prompt double J/ψ hadroproduction performed by the LHCb [9] and CMS [10] Collaborations at the LHC, and the D0 Collaboration [11] at the Fermilab Tevatron. This is a particularly sensitive testing ground for NRQCD factorization, which takes effect there twice, and a topic of old vintage, pioneered by Ref. [12] in 1995, which has attracted considerable theoretical interest since then (see, e.g., Refs. [13–19]), but is much less advanced than single J/ψ production. So far, only the CS contribution due to $gg \to 2c\bar{c}({}^3S_1^{[1]})$ and the CO contribution due to $gg \to 2c\bar{c}({}^3S_1^{[8]})$, which resembles double fragmentation [see Fig. 1(d)], have been studied for direct J/ψ production and also for the feed down from ψ' mesons, which requires no extra calculation [12–19]. These calculations of prompt double J/ψ production, which we henceforth denote as CS* and CO*, respectively, are incomplete because they lack the ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ contributions to J/ψ and ψ' production and the ${}^3P_J^{[1]}$ and ${}^3S_1^{[8]}$ contributions to χ_{cJ} production, where $J = 0, 1, 2$. Interestingly, $J/\psi + \chi_{cJ}$ production is forbidden at $\mathcal{O}(\alpha_s^4)$ in the CS model by CP conservation, while it is enabled by the COM of NRQCD. Thus, we are led to include a total of $\binom{8}{2} - 3 = 25$ different pairings of $c\bar{c}$ Fock states altogether, as indicated in Table I, out of which only 2 have been considered so far. In our Letter, we demonstrate that NRQCD factorization may be reconciled with the experimental data [9–11], leaving room for typical next-to-leading-order (NLO) corrections, if the previously neglected CO and feed-down channels are properly included. We thus add another crucial piece of information to the tantalizing tale of NRQCD factorization [2] and point into a new direction, namely the relative $\mathcal{O}(\alpha_s)$ corrections to the next-to-leading-power (NLP) and next-to-next-to-leading-power (NNLP) CO processes of prompt double J/ψ hadroproduction to be identified below. If their inclusion turned out to bring the NRQCD prediction in agreement with the LHC data, which we deem very likely for reasons explained below, this would be an important milestone in the verification of the COM, which is a key prediction of NRQCD factorization. Owing to the predicted LDME universality, double J/ψ production will then also yield independent constraints on yield and polarization of single J/ψ production.

Our Letter also suggests a solution to another important QCD problem of general interest [20], namely the double-parton-scattering (DPS) surplus observed by the D0 Collaboration [11]. In fact, their result for $\sigma_{\mathrm{eff}} = (\sigma_{J/\psi})^2/\sigma_{\mathrm{DPS}}$ is considerably smaller than the findings by other experiments [11]. The increase of the single-parton-scattering (SPS) portion σ_{SPS} due to our completion of the NRQCD prediction results in a reduction of σ_{DPS}, which in turn increases σ_{eff} and so places it in the

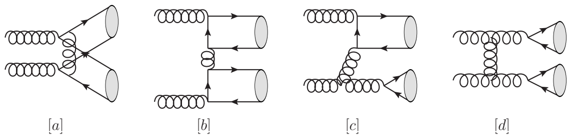

FIG. 1: Typical Feynman diagrams for $gg \to c\bar{c}(m)c\bar{c}(n)$: (a) nonfragmentation type I, (b) nonfragmentation type II, (c) single-fragmentation-like, (d) double-fragmentation-like.

ball park of other determinations.

So far, the experimental data [9–11], which come as total cross sections $\sigma_{\rm tot}$ and distributions in the invariant mass M, the transverse momentum P_T, and the rapidity (y) separation $|\Delta y|$ of the J/ψ pair, have mostly been compared with CS* predictions, which dominate for small values of the J/ψ transverse momentum p_T [13–15], while the CO* contributions take over in the large-p_T region, for $p_T \gtrsim 16$ GeV at the LHC [16]. In the LHCb [9] case, the CS* prediction for $\sigma_{\rm tot}$, which receives a moderate enhancement of relative order $\mathcal{O}(\alpha_s)$ of about 10% [19], is compatible with the measurement, but the one for the distribution $d\sigma/dM$ significantly overshoots the data points close to the J/ψ pair production threshold, even after including the negative corrections of relative order $\mathcal{O}(v^2)$, which are about -23% [18]. In the CMS [10] case, the CS* prediction for $\sigma_{\rm tot}$, which is enhanced by more than 1 order of magnitude by relative $\mathcal{O}(\alpha_s)$ corrections [19], can only account for about 2/3 of the measurement, the one for the distribution $d\sigma/dP_T$ significantly differs from the measurement as for the line shape, and the one for $d\sigma/dM$ dramatically undershoots the measurement, by 4 orders of magnitude in the large-M region, for $M > 35$ GeV. This enormous discrepancy seriously jeopardizes the validity of NRQCD factorization [2], and it is an important task of general interest to perform a systematic study of all the contributing channels, which is the very purpose of our Letter. In the D0 [11] case, there is also a large gap between the CS* prediction and the experimental result for the SPS cross section [11].

Owing to the factorization theorems of the QCD parton model and NRQCD, the prompt double J/ψ hadroproduction cross section may be evaluated as

$$\begin{aligned} d\sigma(AB \to 2J/\psi + X) = & \sum_{i,j,m,n,H_1,H_2} \int dx_1 dx_2 \\ & \times f_{i/A}(x_1) f_{j/B}(x_2) d\hat{\sigma}(ij \to c\bar{c}(m)c\bar{c}(n) + X) \\ & \times \langle \mathcal{O}^{H_1}(m) \rangle \mathrm{Br}(H_1 \to J/\psi + X) \\ & \times \langle \mathcal{O}^{H_2}(n) \rangle \mathrm{Br}(H_2 \to J/\psi + X), \end{aligned} \tag{1}$$

where $f_{i/A}(x)$ is the parton distribution function (PDF) of parton i in hadron A, $d\hat{\sigma}[ij \to c\bar{c}(m)c\bar{c}(n) + X]$ is the SDC, $\langle \mathcal{O}^H(m) \rangle$ is the LDME of $H = J/\psi, \chi_{cJ}, \psi'$, and $\mathrm{Br}(H \to J/\psi + X)$ is the branching fraction with the understanding that $\mathrm{Br}(H \to J/\psi + X) = 1$ if $H = J/\psi$. Since the $q\bar{q}$-initiated subprocesses are greatly suppressed

TABLE I: Scaling with p_T and v of $d\sigma/dp_T^2$ for $gg \to c\bar{c}(m)c\bar{c}(n)$ times the respective LDMEs and branching fractions for the relevant pairings (m,n) of $c\bar{c}$ Fock states. Note that ${}^3P_J^{[1]}$ are counted separately for $J = 0, 1, 2$.

(m,n)	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$	${}^3P_J^{[1]}$
${}^3S_1^{[1]}$	$1/p_T^8$	v^4/p_T^8	v^3/p_T^8	v^4/p_T^8	0
${}^3S_1^{[8]}$	$\cdots$	v^8/p_T^4	v^7/p_T^6	v^8/p_T^6	v^8/p_T^6
${}^1S_0^{[8]}$	$\cdots$	$\cdots$	v^6/p_T^8	v^7/p_T^8	v^7/p_T^8
${}^3P_J^{[8]}$	$\cdots$	$\cdots$	$\cdots$	v^8/p_T^8	v^8/p_T^8
${}^3P_J^{[1]}$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	v^8/p_T^8

by the light-quark PDFs [15], we concentrate on gg fusion. Because of the smallness of $\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) = 1.27\%$ [21], we neglect the contributions from $H = \chi_{c0}$. Our analytic results for the CS* and CO* channels agree with the literature [13, 16].

There is a total of 72 Feynman diagrams contributing to the generic partonic subprocess $gg \to c\bar{c}(m)c\bar{c}(n)$, and representative ones are depicted in Fig. 1. For given m and n, not all of them contribute due to J^{PC} conservation. According to the scaling $d\sigma/dp_T^2 \propto 1/p_T^N$ and the topologies of the contributing Feynman diagrams [see Figs. 1(a)–(d)], we divide the partonic subprocesses into 4 categories: (i) NNLP-I, with $N = 8$, including $m = {}^3S_1^{[1]}$ and $n = {}^3S_1^{[1,8]}, {}^1S_0^{[8]}, {}^3P_J^{[8]}$; (ii) NNLP-II, with $N = 8$, too, including $m, n = {}^1S_0^{[8]}, {}^3P_J^{[8]}, {}^3P_J^{[1]}$; (iii) NLP, with $N = 6$, including $m = {}^3S_1^{[8]}$ and $n = {}^1S_0^{[8]}, {}^3P_J^{[8]}, {}^3P_J^{[1]}$; and (iv) leading power (LP), with $N = 4$, including $m = n = {}^3S_1^{[8]}$. While the NNLP-I and NNPL-II subprocesses exhibit the same p_T scaling, they differ by the topologies of the respective Feynman diagrams. In the latter case, these are the diffractionlike ones as in Fig. 1(b), which allow for large values of $|\Delta y|$ and thus for an enhancement of the cross section at large values of M. Also taking into account the scaling with v of the LDMEs and noticing that $\mathrm{Br}(\chi_{c1,2} \to J/\psi\gamma) = \mathcal{O}(v^2)$ numerically, we roughly estimate the relative importance of each channel at large values of p_T as summarized in Table I.

We work at leading order (LO) in the fixed-flavor-number scheme with 3 massless quark flavors and a charm-quark mass of $m_c = 1.5$ GeV. We use the LO formula for $\alpha_s^{(4)}(\mu_r)$ with asymptotic scale parameter $\Lambda^{(4)} = 192$ MeV [22] and the CTEQ5L set of LO proton PDFs [22]. We choose the renormalization and factorization scales as $\mu_r = \mu_f = \xi\sqrt{(4m_c)^2 + p_T^2}$ and vary ξ between 1/2 and 2 about the default value 1 to estimate the theoretical uncertainty. As for the LDMEs of the J/ψ, χ_{cJ}, and ψ' mesons, we adopt the CS values from Ref. [23], evaluated using the Buchmüller-Tye potential, and the CO values from Ref. [24], fitted to single J/ψ hadroproduction data at LO in NRQCD. Because of the strong correlations between $\langle \mathcal{O}^H({}^1S_0^{[8]}) \rangle$ and $\langle \mathcal{O}^H({}^3P_0^{[8]}) \rangle$ for $H = J/\psi, \psi'$, only the linear combina-

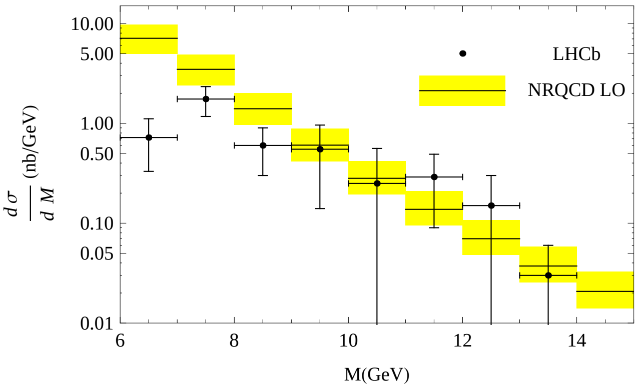

FIG. 2: The M distribution of prompt double J/ψ hadroproduction measured by LHCb [9] is compared to the full LO NRQCD prediction (solid lines). The theoretical uncertainty is indicated by the shaded (yellow) bands.

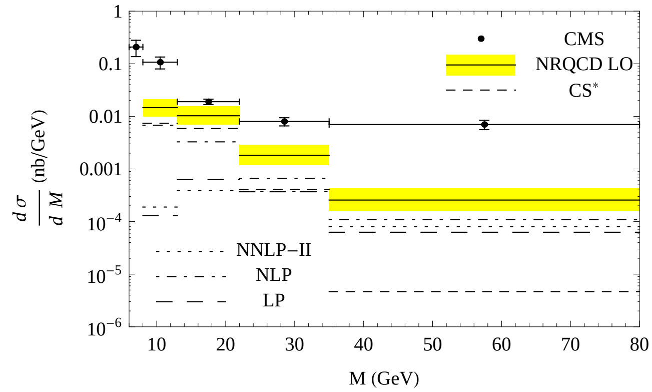

FIG. 3: The M distribution of prompt double J/ψ hadroproduction measured by CMS [10] is compared to the full LO NRQCD prediction (solid lines), its NNLP-II (dotted lines), NLP (dot-dashed lines), and LP (long-dashed lines) components, and the LO CS* contribution (dashed lines). The theoretical uncertainty in the LO NRQCD prediction is indicated by the shaded (yellow) bands.

tions $M_r^H = \langle \mathcal{O}^H(^1S_0^{[8]})\rangle + r\langle \mathcal{O}^H(^3P_0^{[8]})\rangle/m_c^2$ could be determined in Ref. [24]. Fortunately, these correlations are very similar in prompt double J/ψ hadroproduction via the NNLP-II and NLP subprocesses. We use $\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 33.9\%$, $\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 19.2\%$, and $\mathrm{Br}(\psi' \to J/\psi + X) = 60.9\%$ [21].

Prior to performing detailed comparisons with measurements, we expose some general features of our results. (a) Among the NNLP-I subprocesses, no kinematic enhancements are found relative to the CS* channel, so that all the other channels are suppressed as $\mathcal{O}(v^3)$ by the LDMEs. (b) Although the p_T scaling of the NNLP-II subprocesses is as unfavorable as that of the NNLP-I ones, their SDCs may be about 50–200 times larger than that of the CS* channel. (c) The contribution of the NLP subprocesses may also exceed that of the CS* channel, e.g., for $p_T > 20$ GeV under CMS kinematic conditions. (d) At large values of M, the M scalings and the corresponding p_T scalings of the 4 types of subprocesses are the same, but the differential cross sections $d\sigma/dM$ of the NNLP-II, NLP, and LP subprocesses may be more than 1 order of magnitude larger than that of the CS* channel. Observations (b)–(d) indicate that the combination of the CS* and CO* contributions, $d\sigma^*$, may not be a good approximation to the full NRQCD result, $d\sigma$, especially at large values of M. (e) As expected from identical-boson symmetry and the $J/\psi + \chi_{cJ}$ suppression mentioned above, the relative importance of the χ_{cJ} (ψ') feed-down contribution is reduced (increased) with respect to prompt single J/ψ hadroproduction.

The LHCb Collaboration [9] measured σ_{tot} at center-of-mass (CM) energy $\sqrt{s} = 7$ TeV requiring $p_T < 10$ GeV and $2.0 < y < 4.5$ for each of the J/ψ mesons to find $\sigma_{\mathrm{tot}}^{\mathrm{LHCb}} = (5.1 \pm 1.0 \pm 1.1)$ nb. Our corresponding LO NRQCD predictions are $\sigma_{\mathrm{tot}}^* = 12.2^{+4.8}_{-3.8}$ nb, which is somewhat larger than in Refs. [18, 19] because of different choices of m_c, LDMEs, PDFs, and scales, and $\sigma_{\mathrm{tot}} = 13.2^{+5.2}_{-4.1}$ nb, which is about 2.6 times larger than the LHCb result. To better understand the origin of this excess, we consider in Fig. 2 the LHCb and full LO NRQCD results differential in M. We observe that the theoretical prediction systematically overshoots the experimental data in the threshold region, where $M \lesssim 9$ GeV, while there is nice agreement for larger values of M. Near the J/ψ pair production threshold, multiple soft-gluon emissions spoil the perturbative treatment, relativistic corrections are nonnegligible [25], and $\sigma_{\mathrm{tot}} \propto m_c^{-8}$ [18], which amplifies the theoretical uncertainty. All these effects are likely to render a LO NRQCD analysis inappropriate there.

The CMS data [10] were taken at the same CM energy, but are subject to a y-dependent low-p_T cut and cover a more central y range than the LHCb data, as specified in Eq. (3.3) of Ref. [10]. They yield $\sigma_{\mathrm{tot}}^{\mathrm{CMS}} = (1.49 \pm 0.07 \pm 0.13)$ nb. Our LO NRQCD predictions are $\sigma_{\mathrm{tot}}^* = 0.10^{+0.05}_{-0.03}$ nb and $\sigma_{\mathrm{tot}} = 0.15^{+0.08}_{-0.05}$ nb, which is still 1 order of magnitude smaller than the CMS measurement. The NNLP-I, NNLP-II, NLP, and LP contributions to the central value of σ_{tot} are 97, 13, 27, and 14 fb, respectively. I.e., over 36% of σ_{tot} is made up by the NNLP-II, NLP, and LP processes; about one half of this contribution comes as feed down from χ_{cJ} mesons, via $J/\psi + \chi_{cJ}$ and $\chi_{cJ} + \chi_{cJ}$. Therefore, the CS* approximation is bound to be insufficient, even after including the $\mathcal{O}(\alpha_s)$ corrections [19]. To substantiate this statement, we also consider the scaling $d\sigma/dp_T^2 \propto 1/p_T^N$. In the CS* channel, we have $N = 8$ at LO and $N = 6$ at NLO [19, 26]. Similarly, the NNLP-II and NLP processes at NLO are expected to have $N = 6$ and $N = 4$, respectively, and are thus likely to produce sizable enhancements as well. Correction factors of 5–10, which appear plausible, would eliminate the discrepancy between the CMS measurement of σ_{tot} and the NRQCD prediction.

The CMS Collaboration also measured the differential cross section in bins of M and $|\Delta y|$. As mentioned above, the $\mathcal{O}(\alpha_s)$-corrected CS* prediction for $d\sigma/dM$ [19] dramatically undershoots the CMS data at large values of M, by about 2 and 4 orders of magnitude in the two outmost bins 22 GeV $< M <$ 35 GeV and 35 GeV $< M <$ 80 GeV, respectively. In Fig. 3, we confront these CMS data with our full LO NRQCD result also showing the LO CS*, NNLP-II, NLP, and LP contributions for reference. We observe that the previously neglected NRQCD contributions greatly help to fill the gap between data and theory. After their inclusion, the LO NRQCD predictions are only about 4 and 30 times smaller than the CMS data in the last two bins, where the NNLP-II, NLP, and LP processes are approximately equally important.

At LO, M, p_T, and $|\Delta y|$ are not independent of each other, but related by $M = 2\sqrt{4m_c^2 + p_T^2}\cosh(|\Delta y|/2)$. Thus, the significant enhancement in the M distribution may be understood from the $|\Delta y|$ distribution, which is shown in Fig. 4. We observe from Fig. 4 that the CS* contribution to $d\sigma/d|\Delta y|$ peaks near $|\Delta y| = 0$, which implies that the bulk of the CS* contribution to $d\sigma/dM$ at $M \gg 2m_{J/\psi}$ arises from the large-p_T region, with $p_T \approx M/2$, where the cross section is already very small. On the other hand, Fig. 4 tells us that the inclusion of the residual LO NRQCD contributions renders the $|\Delta y|$ distribution significantly broader, which in turn allows for the moderate-p_T region to feed into the large-M bins so as to increase $d\sigma/dM$ there by orders of magnitude. Detailed inspection of the SDCs reveals that the broadening of the $d\sigma/d|\Delta y|$ peak about $|\Delta y| = 0$ is produced by the pseudodiffractive topologies of Feynman diagrams, with a t-channel gluon exchange, like those in Figs. 1(b)–(d). Although the agreement between the CMS measurement of $d\sigma/dM$ and the NRQCD prediction is dramatically improved by the inclusion of the missing LO contributions, there remain appreciable gaps, of roughly 1 order of magnitude, in the outmost bins in Fig. 3. Because of their slower falloff with p_T in connection with the minimum-p_T cut, the NLO corrections to those new CO and feed-down contributions, which lie beyond the scope of our present analysis, are likely to further improve the situation. That the CMS kinematic conditions give rise to large NLO corrections may also be understood from the P_T distribution in Fig. 2(c) and Table 4 of Ref. [10] by observing that only 19% of $\sigma_{\rm tot}$ arise from the lowest bin $P_T < 5$ GeV, which includes the back-to-back situation of the LO calculation, for which $P_T = 0$. A good part of this bin and all the other bins require the radiation of an additional parton, which only comes at NLO. This also explains why the CS* prediction for $\sigma_{\rm tot}$ receives such a sizable $\mathcal{O}(\alpha_s)$ correction [19].

The LHCb [9] and CMS [10] measurements involve both SPS and DPS contributions. The D0 Collaboration [11] attempted to separate them in their measurement of prompt double J/ψ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with $p_T > 4$ GeV and $|\eta| < 2.0$, where η is the J/ψ pseudorapidity, to find $\sigma_{\rm SPS}^{\rm D0} = (70 \pm 6 \pm 22)$ fb and $\sigma_{\rm DPS}^{\rm D0} = (59 \pm 6 \pm 22)$ fb. The central SPS result

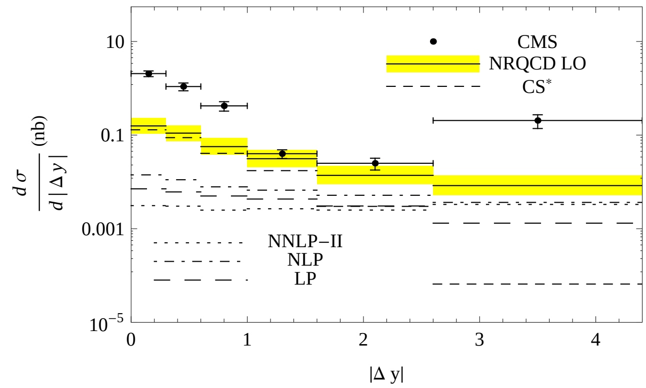

FIG. 4: As in Fig. 3, but for the $|\Delta y|$ distribution.

exceeds the LO CS* prediction $\sigma^*_{\rm tot} = 51.9$ fb [27] by 35%. We estimate the residual LO NRQCD contributions, due to the ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ channels and the feed down from χ_{cJ} mesons considered here, to yield a 28% enhancement, which establishes nice agreement. The situation might change again after including NLO corrections. The cutoff-regularized real radiative corrections of relative order $\mathcal{O}(\alpha_s)$ to the CS* contribution were considered in Ref. [26].

From the comparisons in three different experimental environments, we conclude that, in the small-p_T region and away from the J/ψ pair production threshold, the CS* calculation provides a reasonable approximation to the full NRQCD result and acceptable descriptions of the measurements [9–11]. However, at large values of M and $|\Delta y|$, the CS* contribution to the full NRQCD prediction is small against those due to the NNLP-II, NLP, and LP processes, which have been neglected so far. In fact, their inclusion reduces the gap between the CS* result and the CMS data [10] in the outmost M and $|\Delta y|$ bins by several orders of magnitude, but leave room for NLO corrections of typical size. Should the NLO NRQCD prediction, which is yet to be calculated, agree with the CMS data, then this would provide strong evidence in favor of the COM.

Prompt double J/ψ hadroproduction also serves as a useful laboratory to probe the DPS mechanism [20]. Reportedly, (46 ± 22)% of the D0 result is due to DPS [11]. If the determination of the SPS contribution is only based on the CS* approximation, then the DPS contribution dominates for $|\Delta y| > 2.0$ because of its considerably broader $|\Delta y|$ distribution [20]. However, including the residual NRQCD contributions, due to the NNLP-II, NLP, and LP processes, on top of the CS* contribution renders the $|\Delta y|$ distribution of SPS much broader, as may be seen in Fig. 4 for CMS kinematic conditions, leaving less room for DPS in agreement with other measurements [11]. In other words, the relative importance of SPS and DPS extracted from experimental data delicately depends on the quality of the NRQCD prediction, and any conclusions concerning the significance of DPS are premature before the NLO corrections to all the relevant channels are taken into account.

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