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Probing nonrelativistic QCD factorization in polarized J/ψ photoproduction at next-to-leading order

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Abstract

We analyze the polarization observables of J/ψ photoproduction at next-to-leading order (NLO) within the factorization formalism of nonrelativistic quantum chromodynamics (NRQCD). This is the first NLO study of heavy-quarkonium polarization including the full relativistic corrections due to the intermediate ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$ color-octet (CO) states in the worldwide endeavor to test NRQCD factorization at the quantum level. We present theoretical predictions in the helicity, target, and Collins-Soper frames of DESY HERA, evaluated using the CO long-distance matrix elements previously extracted through a global fit to experimental data of unpolarized J/ψ production, and confront them with recent measurements by the H1 and ZEUS Collaborations. We find the overall agreement to be satisfactory, but the case for NRQCD to be not as strong as for the J/ψ yield.

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The test of NRQCD factorization [1] has been identified to be among the most exigent milestones on the roadmap of heavy-quarkonium physics at the present time [2]. Quarkonia are systems consisting of a quark and its antiparticle bound by the strong force, among which charmonium $c\bar{c}$ and bottomonium $b\bar{b}$ are considered heavy. The J/ψ meson, the lowest-lying $c\bar{c}$ state of spin one, which was simultaneously discovered at the Brookhaven National Laboratory [3] and the Stanford Linear Accelerator Center [4] in November 1974 (The Nobel Prize in Physics 1976), provides a particularly useful laboratory for such a test because it is copiously produced at all high-energy particle colliders, owing to its relatively low mass, and particularly easy to detect experimentally. In fact, sharing the total-angular-momentum, parity, and charge-conjugation quantum numbers $J^{PC} = 1^{--}$ with the photon, it can decay to e^+e^- and $\mu^+\mu^-$ pairs producing spectacular signatures in the detectors, the branching fraction of either decay channel being as large as about 6% [5].

In fact, the NRQCD factorization formalism [1] provides a rigorous theoretical framework for the description of heavy-quarkonium production and decay. This implies a separation of process-dependent short-distance coefficients, to be calculated perturbatively as expansions in the strong-coupling constant α_s, from supposedly universal long-distance matrix elements (LDMEs), to be extracted from experiment. The relative importance of the latter can be estimated by means of velocity scaling rules, which predict each of the LDMEs to scale with a definite power of the heavy-quark ($Q = c, b$) velocity v in the limit $v \ll 1$. In this way, the theoretical predictions are organized as double expansions in α_s and v. A crucial feature of this formalism is that the $Q\overline{Q}$ pair can at short distances be produced in any Fock state $n = {}^{2S+1}L_J^{[a]}$ with definite spin S, orbital angular momentum L, total angular momentum J, and color multiplicity $a = 1, 8$. In particular, this formalism predicts the existence of intermediate CO states in nature, which subsequently evolve into physical, color-singlet (CS) quarkonia by the nonperturbative emission of soft gluons. In the limit $v \to 0$, the traditional CS model (CSM) is recovered in the case of S-wave quarkonia. In the case of J/ψ production, the CSM prediction is based just on the ${}^3S_1^{[1]}$ CS state, while the leading relativistic corrections, of relative order $\mathcal{O}(v^4)$, are built up by the ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$ ($J = 0, 1, 2$) CO states.

The CSM is not a complete theory, as may be understood by noticing that the NLO treatment of P-wave quarkonia is plagued by uncanceled infrared singularities, which are, however, properly removed in NRQCD. This conceptual problem cannot be cured from within the CSM, neither by proceeding to higher orders nor by invoking k_T factorization *etc.*. As it were, NRQCD factorization, appropriately improved at large transverse momenta p_T by systematic expansion in powers of m_Q^2/p_T^2 [6], is the only game in town, which makes its experimental verification such a matter of paramount importance and general interest [2].

The present status of testing NRQCD factorization in charmonium production is as follows. Very recently, NRQCD factorization has been consolidated at NLO by a global fit [7] to all available high-quality data of inclusive unpolarized J/ψ production, comprising a total of 194 data points from 26 data sets collected by 10 experiments at 6 colliders, namely by Belle at KEKB; DELPHI at LEP II; H1 and ZEUS at HERA I and II; PHENIX at RHIC; CDF at Tevatron I and II; and ATLAS, CMS, ALICE, and LHCb at the LHC. This fit successfully pinned down the three CO LDMEs in compliance with the velocity scaling rules, establishing their universality, and yielded an overall description of the data well within the theoretical uncertainties; appreciable deviations arose only in the case of two-photon scattering, where the useable data comprises only 16 events and has not been confirmed by any of the other three LEP II experiments, however. On the other hand, the NLO CS predictions were found to significantly undershoot all the measurements, except for the single data point of e^+e^- annihilation.

In contrast to the J/ψ yield, NRQCD interpretations of J/ψ polarization measurements have so far been exhibiting a rather confusing pattern [2], presumably because the theoretical status is much less advanced there. In fact, complete NRQCD predictions for J/ψ polarization observables so far only exist at LO. At NLO, the CSM predictions for direct photoproduction [8,9] and hadroproduction [10] as well as the ${}^1S_0^{[8]}$ and ${}^3S_1^{[8]}$ contributions to hadroproduction [11], which may be obtained using standard techniques, are known. The NLO calculation of ${}^3P_J^{[8]}$ contributions, which are expected to be significant, is far more intricate because the applications of the respective projection operators to the short-distance scattering amplitudes produce particularly lengthy expressions involving complicated tensor loop integrals and exhibiting an entangled pattern of infrared singularities. This technical bottleneck is overcome here for the first time for J/ψ polarization observables.

Recent high-quality measurements by the H1 [12] and ZEUS [13] Collaborations at HERA provide a strong motivation for us to start by studying photoproduction, where the incoming leptons interact with the protons via quasi-real photons, of low virtuality $Q^2 = -p_\gamma^2$, and are deflected under small angles. Such quasi-real photons participate in the hard scattering either directly or via partons into which they fluctuate (resolve) intermittently. However, resolved photoproduction is greatly suppressed, to the level of 1% [7], by the cut $z > 0.3$ (0.4) applied by H1 [12] (ZEUS [13]) and is thus neglected here. Here, $z = (p_{J/\psi} \cdot p_p)/(p_\gamma \cdot p_p)$, with $p_{J/\psi}$, p_γ, and p_p being the four-momenta of the J/ψ meson, photon, and proton, respectively, denotes the inelasticity variable, which measures the fraction of photon energy transferred to the J/ψ meson in the proton rest frame. Another important variable of photoproduction is the γp invariant mass, $W = \sqrt{(p_\gamma + p_p)^2}$.

The polarization of the J/ψ meson is conveniently analyzed experimentally by measuring the angular distribution of its leptonic decays, which is customarily parametrized using the three polarization observables λ, μ, and ν, as [14]

$$\frac{d\Gamma(J/\psi \to l^+l^-)}{d\cos\theta\, d\phi} \propto 1 + \lambda \cos^2\theta + \mu \sin(2\theta)\cos\phi + \frac{\nu}{2}\sin^2\theta\cos(2\phi), \quad (1)$$

where θ and ϕ are respectively the polar the azimuthal angles of l^+ in the J/ψ rest frame. This definition, of course, depends on the choice of coordinate frame. Among the most frequently employed coordinate frames are the helicity (recoil), Collins-Soper, and target

$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	$(3.04 \pm 0.35) \times 10^{-2}$ GeV^3
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	$(1.68 \pm 0.46) \times 10^{-3}$ GeV^3
$\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	$(-9.08 \pm 1.61) \times 10^{-3}$ GeV^5

Table 1: J/ψ NLO CO LDMEs corrected for feed-down [7].

frames, in which the polar axes point in the direction of $-(\vec{p}_\gamma + \vec{p}_p)$, $\vec{p}_\gamma/|\vec{p}_\gamma| - \vec{p}_p/|\vec{p}_p|$, and $-\vec{p}_p$, respectively. The values $\lambda = 0, +1, -1$ correspond to unpolarized, fully transversely polarized, and fully longitudinally polarized J/ψ mesons, respectively.

On the theoretical side, we have

$$\begin{aligned}\lambda &= \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}},\\ \mu &= \frac{\sqrt{2}\mathrm{Re}\, d\sigma_{10}}{d\sigma_{11} + d\sigma_{00}},\\ \nu &= \frac{2d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}},\end{aligned} \tag{2}$$

where $d\sigma_{ij}$, with $i, j = 0, \pm 1$ denoting the z component of S, is the ij component of the $ep \to J/\psi + X$ differential cross section in the spin density matrix formalism. Invoking the Weizsäcker-Williams approximation and the factorization theorems of the QCD parton model and NRQCD [1], we have

$$\begin{aligned} d\sigma_{ij} = \sum_{k,n} \int & dx dy\, f_{\gamma/e}(x) f_{k/p}(y) \langle \mathcal{O}^{J/\psi}[n] \rangle \\ & \times \frac{1}{2s} d\mathrm{PS}\, \overline{\rho_{ij}(\gamma k \to c\overline{c}[n] + X)}, \end{aligned} \tag{3}$$

where $f_{\gamma/e}(x)$ is the photon flux function, $f_{k/p}(y)$ the parton distribution function (PDF) of parton $k = g, q, \overline{q}$ with $q = u, d, s$, $\langle\mathcal{O}^{J/\psi}[n]\rangle$ are the LDMEs, $s = (p_\gamma + p_k)^2$, and dPS is the phase space measure of the outgoing particles. The spin density matrix elements of the partonic cross sections, $\rho_{ij}(\gamma k \to c\overline{c}[n] + X)$, are averaged (summed) over the spins and colors of the incoming (outgoing) particles, keeping i and j fixed for the $c\overline{c}$ pair in Fock state n. The quantities ρ_{ij} are evaluated by applying polarization and color projectors similar to those listed in Ref. [15] to the squared QCD matrix elements of open $c\overline{c}$ production. For $n = {}^3S_1^{[1]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$, the $c\overline{c}[n]$ spin polarization vectors $\epsilon(i)$ appearing in ρ_{ij} are replaced by their explicit expressions [16]. In the case of $n = {}^3P_J^{[8]}$, for which $S = L = 1$, the z components of L are summed over. For $n = {}^1S_0^{[8]}$, ρ_{11} and ρ_{00} are each set to one third of the squared matrix element, and $\rho_{10} = \rho_{1,-1} = 0$. For space limitation, we refrain from presenting here more technical details, but refer the interested reader to a forthcoming publication.

We now describe the theoretical input for our numerical analysis. In all our NRQCD calculations, we use the CO LDME set extracted in Ref. [7] after subtracting from the

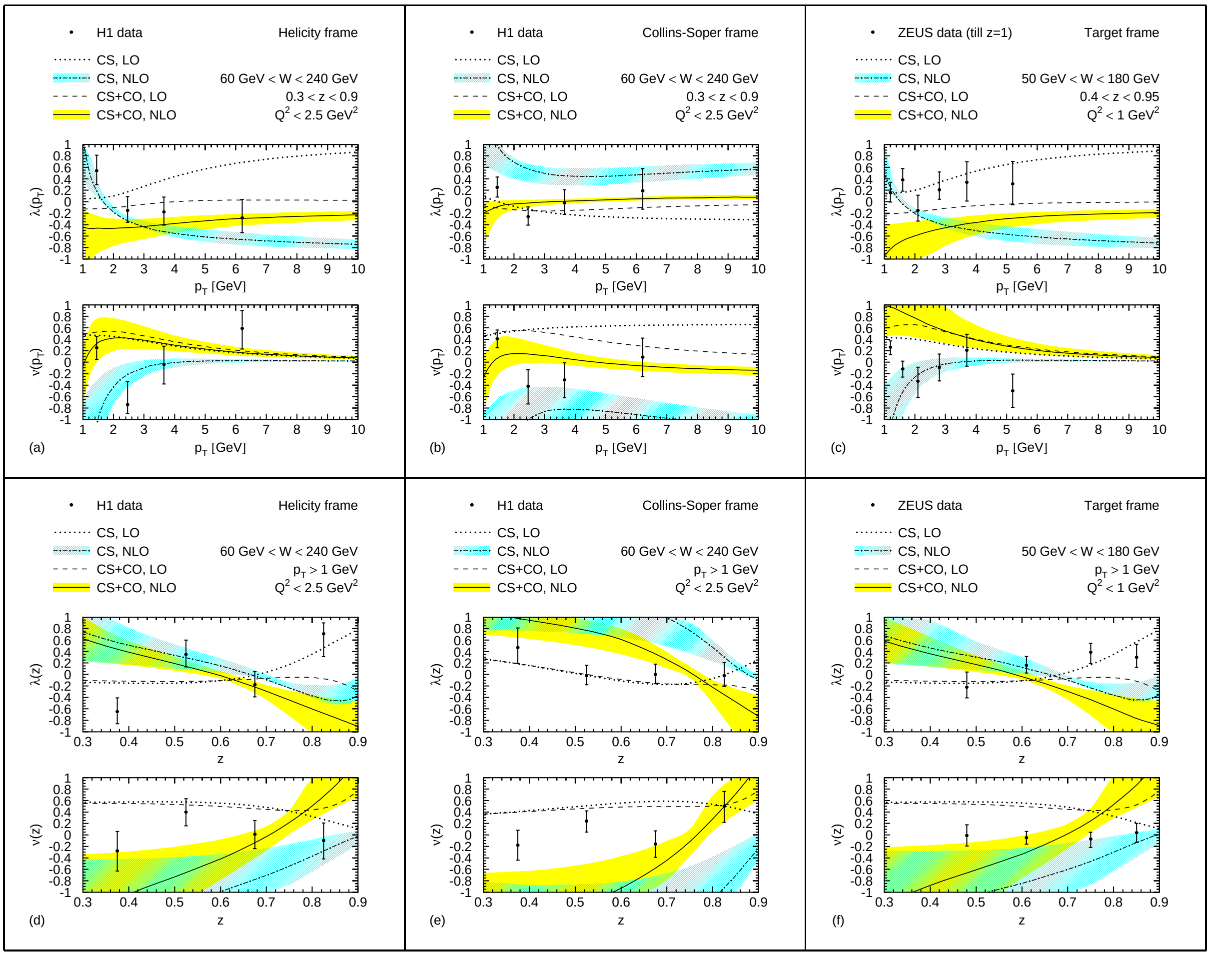

Figure 1: (color online) NLO NRQCD predictions (solid lines) for λ and ν as functions of p_T and z in the helicity, Collins-Soper, and target frames including theoretical uncertainties (shaded/yellow bands) compared to H1 [12] and ZEUS [13] data. For comparison, also the NLO CSM (dot-dashed lines) predictions including theoretical uncertainties (hatched/blue bands) as well as the LO NRQCD (dashed lines) and LO CSM (dotted lines) ones are shown.

data fitted to the estimated contributions due to feed-down from heavier charmonia. For the reader's convenience, these values are listed in Table 1. For consistency, we also adopt the residual input from Ref. [7]. In particular, we choose the CS LDME to be $\langle\mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle = 1.32\ \mathrm{GeV}^3$ [17] and the charm-quark mass, which we renormalize according to the on-shell scheme, to be $m_c = 1.5$ GeV, adopt the values of the electron mass m_e and the electromagnetic coupling constant α from Ref. [5], and use the one-loop (two-loop) formula for $\alpha_s^{(n_f)}(\mu_r)$, with $n_f = 4$ active quark flavors, at LO (NLO). As for the proton PDFs, we use the CTEQ6L1 (CTEQ6M) set [18] at LO (NLO), which comes with an asymptotic scale parameter of $\Lambda_{\mathrm{QCD}}^{(4)} = 215$ MeV (326 MeV). We evaluate the photon flux function using Eq. (5) of Ref. [19]. Our default choices for the $\overline{\mathrm{MS}}$ renormalization, factorization, and NRQCD scales are $\mu_r = \mu_f = m_T$ and $\mu_\Lambda = m_c$, respectively, where $m_T = \sqrt{p_T^2 + 4m_c^2}$ is the J/ψ transverse mass. The bulk of the theoretical uncertainty is due to the lack of knowledge of corrections beyond NLO, which are estimated by varying μ_r, μ_f, and μ_Λ by a factor 2 up and down relative to their default values. In our NLO NRQCD predictions, we must also include the errors in the CO LDMEs. To this end, we determine the maximum upward and downward shifts generated by independently varying their values according to Table 1 and add the resulting half-errors in quadrature to those due to scale variations.

In Fig. 1, we compare our NLO NRQCD predictions for λ and ν as functions of p_T and z, evaluated from Eq. (2) with the respective differential cross sections inserted on the r.h.s., with the measurements by H1 [12] in the helicity and Collins-Soper frames and by ZEUS [13] in the target frame. The H1 data was taken during the years 2006 and 2007, and corresponds to an integrated luminosity of 165 pb^{-1}, while the ZEUS analysis covers all data collected from 1996 through 2007, corresponding to 430 pb^{-1}. At HERA, 27.5 GeV electrons or positrons were colliding with 820 GeV (920 GeV) protons before (since) 1998. As the admixture of 820 GeV protons in the ZEUS data sample is negligible, we take the c.m. energy to be 318 GeV also there. We adopt the experimental acceptance cuts, indicated in each of the six frames of Fig. 1, except for the p_T distribution by ZEUS in Fig. 1(c). Unfortunately, ZEUS did not impose any upper z cut, which poses two problems on the theoretical side. On the one hand, in the kinematic endpoint region, at $z \approx 1$, where the scattering becomes elastic, the cross section is overwhelmed by diffractive J/ψ production, the treatment of which lies beyond the scope of our paper. On the other hand, the NRQCD expansion in v breaks down in the limit $z \to 1$, so that our fixed-order calculation becomes invalid. We avoid these problems by introducing the cut $z < 0.95$, accepting that the comparison with the ZEUS data then has to be taken with a grain of salt.

For comparison, also the LO NRQCD as well as the LO and NLO CSM predictions are shown in Fig. 1. In order to visualize the size of the NLO corrections to the hard-scattering cross sections, the LO predictions are evaluated with the same LDMEs. We observe that, in all the cases considered, the inclusion of the NLO corrections has a considerably less dramatic effect in NRQCD than in the CSM, where the normalizations and shapes of the various distributions are radically modified. This indicates that the perturbative expansion in α_s converges more rapidly in NRQCD than in the CSM. Looking at the $\lambda(p_T)$ distributions in Figs. 1(a)–(c), we notice that NRQCD predicts large-p_T J/ψ mesons to be approximately unpolarized, both at LO and NLO, which is nicely confirmed by the H1 measurements in Figs. 1(a) and (b). However, the ZEUS measurement in Fig. 1(c), which reaches all the way up to $z = 1$, exhibits a conspicuous tendency towards transverse polarization, which might well reflect the notion that diffractively produced vector mesons prefer to be strongly transversely polarized at $z \approx 1$ [20]. Comparing the NLO NRQCD and CSM predictions in the three different frames, we conclude that the Colins-Soper frame possesses the most discriminating power. As expected, the theoretical uncertainties, which are chiefly due to scale variations, steadily decrease as the value of p_T increases, which just reflects asymptotic freedom. By the same token, the theoretical uncertainties in the z distributions in Figs. 1(d)–(e), which are dominated by contributions from the p_T region close to the lower cut-off at $p_T = 1$ GeV, are quite sizable, which makes a useful interpretation of the experimental data more difficult.

At this point, we compare our results with the theoretical literature. We agree with the LO NRQCD formulas for $\overline{\rho_{ij}(\gamma k \to c\overline{c}[n] + k)}$ listed in Appendix B of Ref. [16]. We are able to nicely reproduce the NLO CSM results for λ and ν as functions of p_T and z shown in Fig. 2 of Ref. [8] and Fig. 2 of Ref. [9] if we adopt the theoretical inputs specified there. The differences between those NLO CSM results and the respective results in our Fig. 1 are due to the use of different theoretical inputs. A similar statement applies to the LO NRQCD results graphically displayed in Refs. [12,13,16], which are evaluated using CO LDMEs obtained from LO fits to Tevatron I data.

In contrast to the unpolarized J/ψ yield, where the most precise world data uniformly and vigorously support NRQCD and distinctly disfavor the CSM at NLO [7], the situation seems to be less obvious for the J/ψ polarization in photoproduction, as a superficial glance at Fig. 1 suggests. However, detailed investigation reveals that the overall χ^2 value of all the H1 and ZEUS data in Fig. 1 w.r.t. the default NLO predictions is reduced by more than 50% as the CO contributions are included, marking a general trend towards continued verification of NRQCD factorization. Unfortunately, this is where the legacy of HERA, which was shut down in 2007, ends. With the help of the proposed lepton-proton collider LHeC at CERN, polarized J/ψ photoproduction could be studied more precisely and up to much larger values of p_T. Fortunately, measurements of J/ψ polarization have also been performed in hadroproduction at the Tevatron and will be carried on at the LHC for many years. This is arguably the last frontier in the international endeavor to test NRQCD factorization in charmonium physics.

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