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J/psi polarization analyses in NLO NRQCD

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Nonrelativistic QCD provides a rigorous factorization theorem for heavy quarkonium production and decay. It predicts the universality of nonperturbative long distance matrix elements (LDMEs). In our analysis we test the universality of the $^1S_0$, $^3S_1$, and $^3P_0$ color octet (CO) LDMEs at next-to-leading order in α_s by calculating J/ψ polarization observables in photo- and hadroproduction using LDME values from a global fit to unpolarized production data. We show that the NRQCD predictions for λ_θ in the helicity frame are in disagreement with the precise CDF polarization measurement at the Tevatron in run II. We show that neither our set of CO LDMEs nor the ones proposed in two later J/ψ polarization works is able to describe all the unpolarized J/ψ production data and the CDF run II polarization measurement at the same time.

Xth Quark Confinement and the Hadron Spectrum,
October 8-12, 2012
TUM Campus Garching, Munich, Germany

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	Set A: Do not mind feed-downs	Set B: Subtract feed-downs first
$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	$(4.97 \pm 0.44) \times 10^{-2}$ GeV^3	$(3.04 \pm 0.35) \times 10^{-2}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	$(2.24 \pm 0.59) \times 10^{-3}$ GeV^3	$(1.68 \pm 0.46) \times 10^{-3}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	$(-1.61 \pm 0.20) \times 10^{-2}$ GeV^5	$(-9.08 \pm 1.61) \times 10^{-3}$ GeV^5

Table 1: Results of global fit [2] for the J/ψ CO LDMEs. Set A corresponds to the main fit results. In set B, estimated feed-down contributions from higher charmonium states were subtracted from prompt data prior to fitting (hadroproduction: 36%, photoproduction: 15%, $\gamma\gamma$ scattering: 9%, e^+e^- annihilation: 26%).

1. Introduction

According to the factorization theorem of nonrelativistic QCD (NRQCD) [1], the cross section to produce a heavy quarkonium H factorizes according to

$$\sigma(ab \to H + X) = \sum_n \sigma(ab \to c\bar{c}[n] + X)\langle \mathcal{O}^H[n]\rangle, \tag{1.1}$$

where the $\sigma(ab \to c\bar{c}[n] + X)$ are perturbatively calculated short distance cross sections describing the production of a heavy quark pair (here $c\bar{c}$) in an intermediate Fock state n. The $\langle \mathcal{O}^H[n]\rangle$ are nonperturbative long distance matrix elements (LDMEs), which currently have to be extracted from experiment. NRQCD predicts each of the LDMEs to scale with a definite power of the relative heavy quark velocity v, which serves as an additional expansion parameter besides α_s: In case of $H = J/\psi$, the leading order contribution in the v expansion stems from $n = {}^3S_1^{[1]}$ and equals the traditional color singlet model (CSM) prediction, while the next-to-leading terms are made up by the ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$ color octet (CO) states. In [2] we have at NLO accuracy performed a global fit of these three CO LDMEs to inclusive J/ψ production data from various production mechanisms, see table **??** for the results. The global fit is constrained, and describes all data sufficiently well, except perhaps two-photon scattering. The fit results are in line with the velocity scaling rules of NRQCD, and are practically independent of possible cuts on the transverse momentum. In the next section we will then use the extracted LDMEs to compare the resulting NRQCD predictions for J/ψ photo- and hadroproduction with data. We thus scrutinize the universality of the LDMEs, which is not yet established.

2. Polarization predictions for photo- and hadroproduction

Measuring the polarization of J/ψ means measuring the angular distribution of the two leptons by which it is tagged. This distribution is parameterized via

$$W(\theta,\phi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta)\cos\phi, \tag{2.1}$$

where θ and ϕ are the polar and azimuthal angles of the μ^+ or e^+ in the J/ψ rest frame. This definition does depend on the choice of the coordinate system axes. Among the frequently used coordinate frames are the helicity, the Collins-Soper, and the target frame. In the photoproduction literature, also the convention $\lambda = \lambda_\theta$, $\mu = \lambda_{\theta\phi}$ and $\nu = 2\lambda_\phi$ is used. On the theoretical side, we calculate the parameters λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ via

$$\lambda_\theta = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_\phi = \frac{d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_{\theta\phi} = \frac{\sqrt{2}\mathrm{Re}\, d\sigma_{10}}{d\sigma_{11} + d\sigma_{00}}, \tag{2.2}$$

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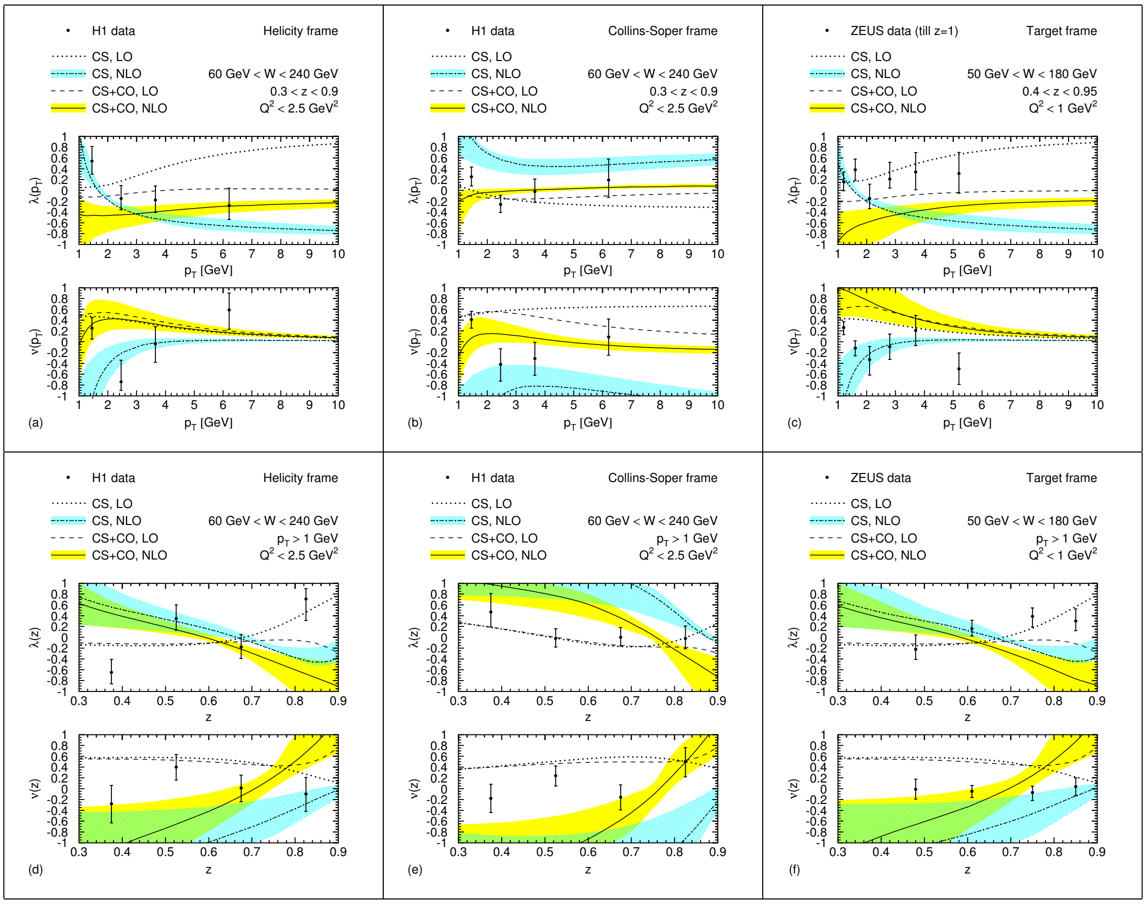

Figure 1: Polarization parameters λ and ν for direct photoproduction at HERA using CO LDME set B of table 1, compared to H1 [4] and ZEUS [5] data. Blue bands: Uncertainties of NLO color singlet (CS) curve due to scale variations. Yellow bands: Uncertainties of NLO CS+CO curve due to scale variations and uncertainties of the CO LDMEs. From [3].

where $d\sigma_{ij}$ are the differential J/ψ production cross sections, calculated using NRQCD factorization, but keeping the spin of the intermediate $c\bar{c}[n]$ pair fixed instead of summing over it. The spin polarization vectors $\varepsilon^*(i)$ in the amplitude and $\varepsilon(j)$ in the complex conjugated amplitude are instead replaced by their explicit expressions.

Our results for direct photoproduction [3] are shown in figure 1. We compare our predictions for the parameters λ and ν as functions of the transverse momentum p_T and the inelasticity variable z with data measured by the H1 [4] collaboration in the helicity and Collins-Soper frames and by the ZEUS collaboration [5] in the target frame. Unfortunately, the H1 [4] and ZEUS [5] data do not yet allow to distinguish the production mechanisms clearly. But kinematical regions can be identified, in which a clear distinction could be possible in more precise experiments at a future ep collider, like the LHeC: At higher p_T, NRQCD predicts the J/ψ to be largely unpolarized in contrast to the CSM predictions. In the z distributions, however, the scale uncertainties are sizable and the error bands of the CSM and NRQCD predictions largely overlap.

Our results for direct hadroproduction [6] are shown in figure 2. We compare our predictions for the parameters λ_θ and λ_ϕ as functions of p_T in the helicity and Collins-Soper frames with the

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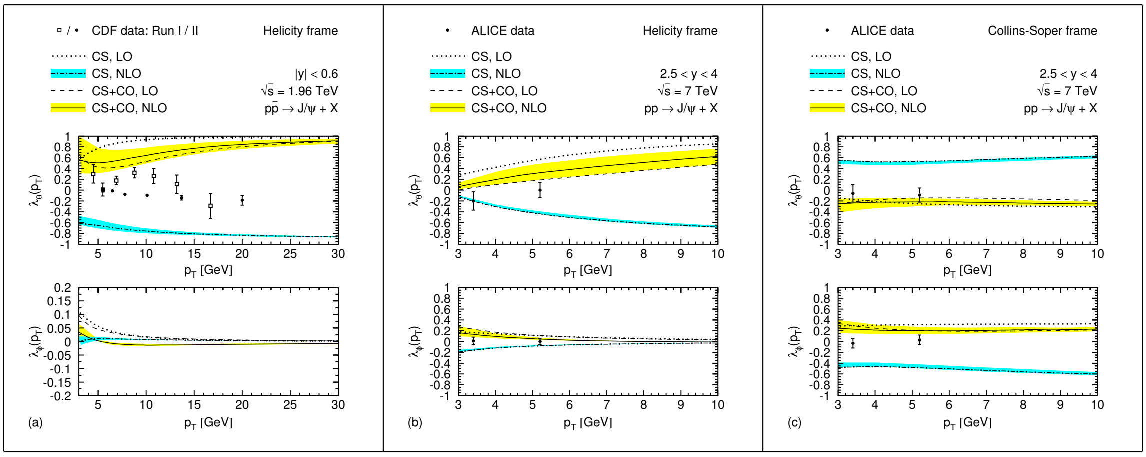

Figure 2: Polarization parameters λ_θ and λ_ϕ for hadroproduction using CO LDME set B of table 1, compared to data measured by CDF at Tevatron in run I [7] and II [8] and by ALICE at the LHC [9]. Blue bands: Uncertainties of NLO CS curve due to scale variations. Yellow bands: Uncertainties of NLO CS+CO curve due to scale variations and uncertainties of the CO LDMEs. From [6].

measurements by CDF [7, 8] and ALICE [9]. In the helicity frame, the CSM predicts strongly longitudinally polarized J/ψ at NLO, while NRQCD predicts a strong transverse polarization. In the Collins-Soper frame the situation is inverted. The precise CDF measurement at Tevatron Run II [8], which is partially in disagreement with the measurement at run I [7], finds largely unpolarized J/ψ in the helicity frame, which is in contradiction to both the CSM and NRQCD predictions. The early ALICE data [9] is however compatible with NRQCD, and favors NRQCD over the CSM.

3. Comparison of three J/ψ production works

Since our publication [6], two other NLO NRQCD analyses involving J/ψ polarization have appeared, which are however limited to hadroproduction: In [10] it was shown that we can describe both the measured J/ψ hadroproduction cross sections and the CDF run II polarization measurement when choosing one of the three CO LDME sets listed in the right part of table 2. On the other hand, the calculation [11] is the first NLO polarization analysis to include feed-down contributions and make polarization predictions for prompt J/ψ, ψ', and χ_{cJ} production. To this end, the CO LDMEs of ψ' and χ_{cJ} were fitted to LHCb (and CDF) unpolarized production data, the resulting cascade decay rates into J/ψ then used as feed-down contributions to determine the J/ψ CO LDMEs in a fit to unpolarized J/ψ production data from LHCb and CDF with $p_T > 7$ GeV. The results predict a moderately transverse J/ψ polarization in the helicity frame.

In order to compare the described calculations, in figure 3, we plot a total e^+e^- cross section, transverse momentum distributions in photo- and hadroproduction, and the polarization observable measured by CDF at the Tevatron in run II [8] using the different sets of CO LDMEs proposed by the different groups. We see that none of the LDME sets can describe all production data. While the CO LDMEs of [6] yield a good description of the unpolarized cross sections, there is a strong disagreement with the CDF II measurement. The CO LDMEs of [10] on the other hand can describe all hadroproduction data, but overshoots the measured e^+e^- and photoproduction cross

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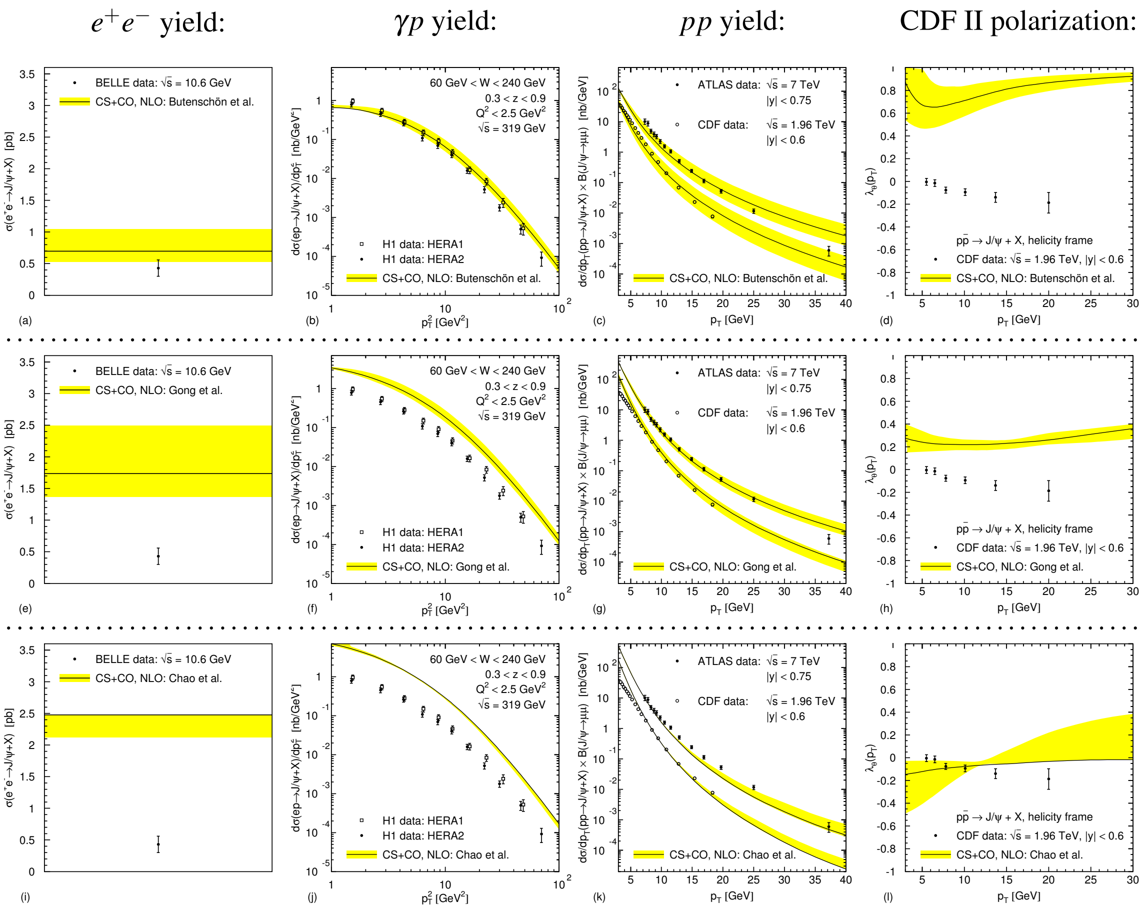

Figure 3: The predictions of the total e^+e^- cross section measured by BELLE [12], the transverse momentum distributions in photoproduction measured by H1 at HERA [13, 4], and in hadroproduction measured by CDF at the Tevatron [14] and ATLAS at the LHC [15], and the polarization parameter λ_θ measured by CDF at the Tevatron in run II [8]. The predictions are plotted using the values of the CO LDMEs given in the publications [6], [11] and [10] and listed in table 2. The error bars of graphs a-g refer to scale variations, for graph d we quadratically add the fit errors according to table 1. Graph h is taken over from Fig. 4 of [11]. As for graphs i-l, the central lines are evaluated with the default set, and the error bars evaluated with the alternative sets of the CO LDMEs used in [10] and listed in table 2.

sections by a factor four till six. The CO LDMEs of [11] yield predictions which are in all cases in between those of the other two options.

4. Conclusions

We perform a test of the universality of the J/ψ CO LDMEs at NLO in α_s by fitting them to global unpolarized production data, and in a second step using the results to predict J/ψ polarization in photo- and hadroproduction. The prediction of strongly transverse helicity frame J/ψ polarization in hadroproduction stands in contrast to the precise CDF run II measurement, which found unpolarized J/ψ. Also using CO LDME sets proposed by two other groups does not help us to reach a sufficient description of all measured precision data. Thus we conclude that the

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	Butenschön, Kniehl [6]:	Gong, Wang, Wan, Zhang [11]:	Chao, Ma, Shao, Wang, Zhang [10]: (default set)	(set 2)	(set 3)
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$	1.32 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3
$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	0.0497 GeV^3	0.097 GeV^3	0.089 GeV^3	0	0.11 GeV^3
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	0.0022 GeV^3	-0.0046 GeV^3	0.0030 GeV^3	0.014 GeV^3	0
$\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	-0.0161 GeV^5	-0.0214 GeV^5	0.0126 GeV^5	0.054 GeV^5	0
$\langle\mathcal{O}^{\psi'}(^3S_1^{[1]})\rangle$		0.758 GeV^3			
$\langle\mathcal{O}^{\psi'}(^1S_0^{[8]})\rangle$		-0.0001 GeV^3			
$\langle\mathcal{O}^{\psi'}(^3S_1^{[8]})\rangle$		0.0034 GeV^3			
$\langle\mathcal{O}^{\psi'}(^3P_0^{[8]})\rangle$		0.0095 GeV^5			
$\langle\mathcal{O}^{\chi_0}(^3P_0^{[1]})\rangle$		0.107 GeV^5			
$\langle\mathcal{O}^{\chi_0}(^3S_1^{[8]})\rangle$		0.0022 GeV^3			

Table 2: The values of the LDMEs used for plotting the graphs of Fig. 3. In [10] three sets of CO LDMEs are used: A default set, and two alternative sets. The analyses [6] and [10] refer only to direct J/ψ production.

universality of the production LDMEs is challenged. Possible remedies would be the following: 1. The awaited new LHC polarization measurements would not confirm the CDF run II results. 2. Currently, photoproduction cross sections are measured up to $p_T = 10$ GeV. Although unlikely, it can not be totally excluded that future experiments would show a drastically weaker slope at even higher p_T, such that the LDME sets of [11] or [10] might yield better agreement with data there. 3. To question the convergence of the v expansion rather than the universality of the LDMEs.

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