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With nonrelativistic QCD factorization, we present a full next-to-leading order computation of the polarization observable for J/ψ production at hadron colliders including all important Fock states, i.e. ${}^3S_1^{[1,8]}$, ${}^1S_0^{[8]}$, and ${}^3P_J^{[8]}$. We find the ${}^3P_J^{[8]}$ channel contributes a positive longitudinal component and a negative transverse component. So the J/ψ polarization puzzle may be understood as the transverse components cancel between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channels, which results in mainly unpolarized (even slightly longitudinally polarized) J/ψ. This may give a possible solution to the long-standing J/ψ polarization puzzle. Predictions for J/ψ polarization at the LHC are also presented.

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Nonrelativistic QCD (NRQCD)[1] is an effective field theory approach for heavy quarkonium. At present, one of the main obstacles of NRQCD is the polarization puzzle of J/ψ hadroproduction[2]. At leading order (LO) in α_s, J/ψ production is dominated by gluon fragmentation to a color-octet (CO) ${}^3S_1^{[8]}$ $c\bar{c}$ pair at high transverse momentum p_T, which leads to transversely polarized J/ψ[3]. But the CDF Collaboration found the prompt J/ψ in its helicity frame to be unpolarized and even slightly longitudinally polarized[4]. Despite of numerous attempts made in the past years, the puzzle still remains.

For unpolarized J/ψ production, important progress has been made in recent years. It was found that the next-to-leading order (NLO) QCD corrections to differential cross sections of ${}^3S_1^{[1]}$ channel can be as large as two orders of magnitude at high p_T[5], while that of ${}^1S_0^{[8]}$ and ${}^3S_1^{[8]}$ channels are small[6]. Furthermore, NLO corrections of the ${}^3P_J^{[1]}$[7] and ${}^3P_J^{[8]}$[8, 9] channels are found to be also very large. These large corrections are well understood because at NLO the differential cross section $\mathrm{d}\sigma/\mathrm{dp_T}$ receives contributions from new topologies that scale with p_T in a different manner from the LO calculation. By including NLO corrections, one may explain the existing unpolarized cross sections of p_T up to 70 GeV[7, 8].

Accordingly, it is necessary to examine the J/ψ polarization at NLO. Among various channels, the correction to J/ψ polarization via ${}^3S_1^{[1]}$ channel worked out in [10], which alters the polarization from being transverse at LO to longitudinal at NLO. This phenomenon is explained recently in collinear factorization [11] as next-to-leading power dominance. As for the ${}^3S_1^{[8]}$ channel, the NLO correction can only slightly change the polarization[6], while the ${}^1S_0^{[8]}$ channel gives unpolarized result to all orders in α_s. As a result, the up to date theoretical predictions may indicate a serious puzzle on J/ψ polarization[6]. However, the NLO correction of the ${}^3P_J^{[8]}$ channel to J/ψ polarization has not been calculated. In this letter, we will perform this calculation and show that the NLO contribution of ${}^3P_J^{[8]}$ channel is indeed crucial in clarifying the long-standing J/ψ polarization puzzle in NRQCD.

We first introduce some formalisms in our calculation. The J/ψ can decay into an easily identified lepton pair. The information about the J/ψ polarization is encoded in the angular distributions of the leptons. The two-body leptonic decay angular distribution of J/ψ in its rest frame is usually parameterized as[12]

$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}\cos\theta} \propto 1+\lambda_\theta\cos^2\theta, \lambda_\theta=\frac{\mathrm{d}\sigma_{11}-\mathrm{d}\sigma_{00}}{\mathrm{d}\sigma_{11}+\mathrm{d}\sigma_{00}}. \quad (1)$$

Here, $\mathrm{d}\sigma_{\mathrm{ij}}$ ($i,j=0,\pm1$, with respect to the z components of J/ψ) represents the ij contribution in the spin density matrix formalism. In the literature λ_θ is also denoted as $\alpha=\frac{\mathrm{d}\sigma_\mathrm{T}-2\mathrm{d}\sigma_\mathrm{L}}{\mathrm{d}\sigma_\mathrm{T}+2\mathrm{d}\sigma_\mathrm{L}}$. The differential cross sections are

$$\mathrm{d}\sigma_{\mathrm{s_z s_z}}=\sum_{\mathrm{ijn}}\int \mathrm{dx_1 dx_2} f_{\mathrm{i/H_1}}(\mathrm{x_1},\mu_\mathrm{F}) f_{\mathrm{j/H_2}}(\mathrm{x_2},\mu_\mathrm{F})\langle\mathcal{O}_\mathrm{n}\rangle \mathrm{d}\hat{\sigma}^{\mathrm{ij,n}}_{\mathrm{s_z s_z}}, (2)$$

where $\langle\mathcal{O}_n\rangle$ are the long-distance matrix elements (LDMEs) for $n={}^3S_1^{[1,8]},{}^3P_J^{[8]}$, and ${}^1S_0^{[8]}$. In general, the partonic cross sections $\mathrm{d}\hat{\sigma}^{\mathrm{ij,n}}_{\mathrm{s_z s_z}}$ can be obtained from the spin density matrix elements[12]

$$\rho_{s_z s_z}(ij\to(c\bar{c})[n]X)\propto\sum_{L_z}|\mathcal{M}(ij\to(c\bar{c})[L_z,s_z]X)|^2. (3)$$

In practice, several polarization frame definitions have been used in the literature. In the s-channel helicity frame (HX), the polar axis is chosen as the flight direction of the J/ψ in the laboratory frame. Another frequently used frame is the so-called Collins-Soper frame[13]. For simplicity, here we will only choose HX, the same as used by CDF[4]. The full theoretical predictions of azimuthal correlations and the theoretical descriptions by Collins-Soper, and feeddown from χ_{cJ} and ψ' will be presented in a forthcoming publication.

We describe our method briefly for the sake of completeness. Some improvements are made in our calculations, while the majority of our method has been encompassed in Ref. [8]. The calculations of real corrections are based on the Dyson-Schwinger equations. After absorbing the core codes of the published HELAC[14], we promote it into a form that can generate the matrix element of heavy quarkonia (especially P-wave) production at colliders by adding some P-wave off-shell currents. The virtual corrections are treated analytically, and helicity matrix elements are obtained in spinor helicity method[15].

For numerical results, we choose the same input parameters as in Ref. [8]. Specifically, the renormalization scale μ_r, factorization scales μ_f and NRQCD scale μ_Λ are chosen as $\mu_r = \mu_f = m_T = \sqrt{4m_c^2 + p_T^2}$ and $\mu_\Lambda = m_c$. Scales dependence is estimated by varying $\mu_r, \mu_f, \mu_\Lambda$ by a factor of $\frac{1}{2}$ to 2 respect to their central values. By fitting only cross sections, it was found that only two linear combinations of CO LDMEs can be extracted[8]. Now since the polarization information is also available, we will try to extract the three independent CO LDMEs using the polarization observable λ_θ and production rate $\mathrm{d}\sigma/\mathrm{dp_T}$ of J/ψ measured by CDF Run II [4] simultaneously, where data in low transverse momentum region ($p_T < 7$GeV) are not included in our fit because of existing nonperturbative effects. By minimizing the χ^2, CO LDMEs are obtained and listed in the first row of Tab.I. In Fig.1, we show the comparison of λ_θ between the Tevatron data and our theoretical result.

$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2}GeV^3	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2}GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle/m_c^2$ 10^{-2}GeV^3
1.16	8.9 ± 0.98	0.30 ± 0.12	0.56 ± 0.21
1.16	0	1.4	2.4
1.16	11	0	0

TABLE I: Different sets of CO LDMEs for J/ψ. Values in the first row are obtained by fitting the differential cross section and polarization of prompt J/ψ simultaneously at the Tevatron [4]. Values in the second and third rows are two extreme choices for these CO LDMEs. The CS LDME is calculated by the B-T potential model in [16].

To understand the unpolarized results, λ_θ for each channel is drawn in Fig.2, where for the NLO $^3P_J^{[8]}$ channel we mean the value of $(\mathrm{d}\hat{\sigma}_{11} - \mathrm{d}\hat{\sigma}_{00})/|\mathrm{d}\hat{\sigma}_{11} + \mathrm{d}\hat{\sigma}_{00}|$ because $\mathrm{d}\hat{\sigma}_{11} + \mathrm{d}\hat{\sigma}_{00}$ decreases from being positive to negative as p_T increases. In addition to the known polarization of S-wave[6, 10], the $^3P_J^{[8]}$ channel satisfies $(\mathrm{d}\hat{\sigma}_{11} - \mathrm{d}\hat{\sigma}_{00})/|\mathrm{d}\hat{\sigma}_{11} + \mathrm{d}\hat{\sigma}_{00}| < -1$ in our considered p_T region, which results from $\mathrm{d}\hat{\sigma}_{11} < 0$ and $\mathrm{d}\hat{\sigma}_{00} > 0$. There-

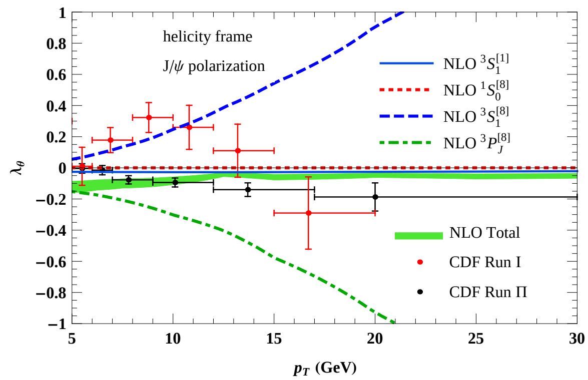

FIG. 1: (color online) NLO results for the polarization observable λ_θ of J/ψ production at the Tevatron. The CDF experimental data are taken from Ref. [4].

fore, the transverse component of $^3P_J^{[8]}$ is negative, which effectively gives a longitudinal contribution to λ_θ, and the longitudinal component of $^3P_J^{[8]}$ is positive. In some parameter space of CO LDMEs, the positive transverse component of $^3S_1^{[8]}$ will largely be canceled by the negative transverse component of $^3P_J^{[8]}$, which yields a small transverse component and results in unpolarized or even longitudinal λ_θ. This explains why the complete NLO calculation gives an unpolarized prediction in Fig.1.

It is interesting to see that, by choosing some proper CO LDMEs, complete NLO predictions in NRQCD factorization can be compatible with data. This is distinct from all previous NRQCD predictions that give strong transverse polarizations for J/ψ[2]. Furthermore, we want to emphasize following four points:

(1) The condition that transverse components with large cancelation between $^3S_1^{[8]}$ and $^3P_J^{[8]}$ determines a specific parameter space for CO LDMEs. Using the same treatment as in [8], we decompose the transverse component of short-distance coefficient of $^3P_J^{[8]}$ into a linear combination of $^3S_1^{[8]}$ and $^1S_0^{[8]}$ as $\mathrm{d}\hat{\sigma}_{11}(^3\mathrm{P}_J^{[8]}) = 2.47\ \mathrm{d}\hat{\sigma}_{11}(^1\mathrm{S}_0^{[8]}) - 0.52\ \mathrm{d}\hat{\sigma}_{11}(^3\mathrm{S}_1^{[8]})$. Since $\mathrm{d}\hat{\sigma}_{11}(^1\mathrm{S}_0^{[8]}) \ll \mathrm{d}\hat{\sigma}_{11}(^3\mathrm{S}_1^{[8]})$ when $p_T > 7$ GeV, the cancelation requirement is approximately equivalent to the absence of the linear combination $\langle\mathcal{O}(^3S_1^{[8]})\rangle - 0.52\ \langle\mathcal{O}(^3P_J^{[8]})\rangle/m_c^2$, which is close to $\mathrm{M}_1 = \langle\mathcal{O}(^3\mathrm{S}_1^{[8]})\rangle - 0.56\langle\mathcal{O}(^3\mathrm{P}_J^{[8]})\rangle/\mathrm{m}_c^2$ defined in [8]. Recall that to have a good fit for unpolarized yield one needs a very small M_1, so conditions for CO LDMEs parameter space introduced by fitting both yield and polarization are consistent with each other. A good agreement with the LHC data for J/ψ cross sections can be found in Fig.3 using the LDMEs in Tab.I.

(2) As the yield and polarization share a common parameter space, and the yield can only constrain two linear combinations of CO LDMEs, the combined fit of both yield and polarization may also not constrain three inde-

pendent CO LDMEs stringently. In fact we find for a wide range of given $\langle\mathcal{O}({}^1S_0^{[8]})\rangle$, one can fit both yield and polarization reasonably well. CO LDMEs under two extreme conditions are listed in Tab.I. When $\langle\mathcal{O}({}^1S_0^{[8]})\rangle$ is chosen to be its maximal value, J/ψ is unpolarized; when $\langle\mathcal{O}({}^1S_0^{[8]})\rangle$ vanishes, λ_θ increases from -0.25 at p_T=5 GeV to 0 at p_T=15 GeV at the Tevatron. Even in these two extreme cases, theoretical predictions of J/ψ cross section and polarization are still close to the Tevatron data, and are also consistent with the observed cross sections by ATLAS[17] and CMS[18] at the LHC as shown in Fig.3. As a result, although it is hard to determine CO LDMEs precisely, we find the polarization puzzle can be much eased for a wide range of $\langle\mathcal{O}({}^1S_0^{[8]})\rangle$ value.

(3) The cancelation of transverse component between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channels is not problematic, since the contribution of an individual channel is unphysical and depends on renormalization scheme and scale[8]. A "physical" requirement is that the summation $\mathrm{d}\sigma_{11}({}^3\mathrm{S}_1^{[8]}+{}^3\mathrm{P}_\mathrm{J}^{[8]})$ should be positive, which is satisfied in the fit.

(4) It is important to note that the LDMEs presented here are significantly different from those extracted from the global fit in [20]. As hadroproduction data play the most important role in [20], this difference cannot mainly be attributed to that the data other than hadroproduction are not considered in our fit. In fact, one can track to the situation where only hadroproduction data are used in the global fit. As explained in [8], our choice of p_T cut for hadroproduction data is $p_T > 7$GeV while the cut in [20] is $p_T > 3$GeV, and our LDMEs can well describe the production p_T distribution in the region $7\mathrm{GeV} < \mathrm{p_T} < 70\mathrm{GeV}$ (see Fig.3), while the fit in [20] puts stress on smaller p_T region and gives too smooth p_T distribution at large p_T. This is the main reason why our LDMEs differ from that in [20]. In our view, for the small p_T region the fixed order perturbation calculation may need to be modified by considering soft gluon emission and other nonperturbative effects. We see that the two treatments in [8] and [20] have different features and should be tested by more experiments in the future.

There are still other uncertainties, such as the charm quark mass, but they do not change the qualitative properties of our result. Predictions of the polarization λ_θ at the LHC with $\sqrt{S}=7$ TeV are plotted in Fig.4, where only forward region ($2 < |y_{J/\psi}| < 3$) and central region ($|y_{J/\psi}| < 2.4$) are considered[1]. The large error bar (yellow bands) in these predictions is caused by lacking knowledge of $\langle\mathcal{O}({}^1S_0^{[8]})\rangle$, thus we scan its all possible values in predictions. It is found in these predictions that λ_θ become sensitive to $\langle\mathcal{O}({}^1S_0^{[8]})\rangle$ when $p_T > 20$ GeV, so it may be possible to extract three independent CO LDMEs when polarization data at high p_T are available.

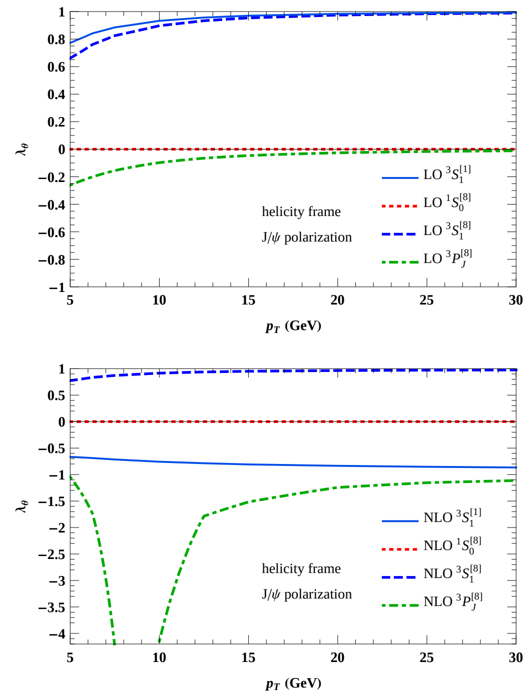

FIG. 2: (color online) The p_T dependence of λ_θ for ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$ channels with $\sqrt{S}=1.96$ TeV and $|y_{J/\psi}| < 0.6$. For the NLO ${}^3P_J^{[8]}$ channel, it means the value of $(\mathrm{d}\hat{\sigma}_{11}-\mathrm{d}\hat{\sigma}_{00})/|\mathrm{d}\hat{\sigma}_{11}+\mathrm{d}\hat{\sigma}_{00}|$.

In summary, we present a full NLO calculation including ${}^3S_1^{[1]}$, ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ for the polarization observable λ_θ of J/ψ in the helicity frame at the Tevatron and LHC. Results of S-wave channels are consistent with those in the literature [10], while that of the ${}^3P_J^{[8]}$ channel are new and play a crucial role in understanding the polarization puzzle. Our calculation shows that the transverse component of ${}^3P_J^{[8]}$ channel is negative, while its longitudinal component is positive. Thus, ${}^3P_J^{[8]}$ channel gives a maximal longitudinal contribution. By choosing suitable CO LDMEs, which bring on a good agreement with the observed J/ψ cross sections at large p_T at the LHC, transverse components can be largely canceled between ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channels, leaving the remaining terms to be dominated by the unpolarized. This may give a possible solution to the long-standing J/ψ polarization puzzle within NRQCD factorization. Although the three independent CO LDMEs are hard to be extracted in an accurate way individually, our interpretation of J/ψ polarization makes sense by using only their combinations. We also present polarization predictions for the LHC.

We thank C. Meng for helpful discussions. This work

[1] Note that ALICE Collaboration has measured J/ψ polarization recently with rapidity $2.5 < |y_{J/\psi}| < 4$[19]. But the measured transverse momenta ($2\mathrm{GeV} < \mathrm{p_T} < 8\mathrm{GeV}$) are smaller than considered in this work.

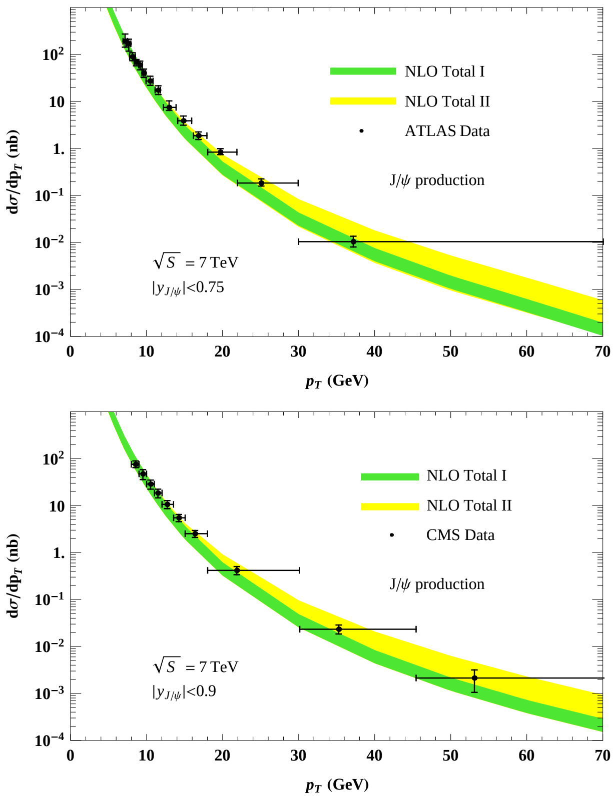

FIG. 3: (color online) Cross sections of J/ψ production at the LHC with LDMEs shown in Tab.I. "NLO Total I" (green bands) correspond to LDMEs in the first row of Tab.I. "NLO Total II" (yellow bands) correspond to LDMEs in the second row: $\langle\mathcal{O}(^1S_0^{[8]})\rangle = 0$ (upper bounds) and third row: $\langle\mathcal{O}(^3S_1^{[8]})\rangle = \langle\mathcal{O}(^3P_J^{[8]})\rangle = 0$ (lower bounds) of Tab.I. ATLAS data are taken from Ref. [17], and CMS data from Ref. [18].

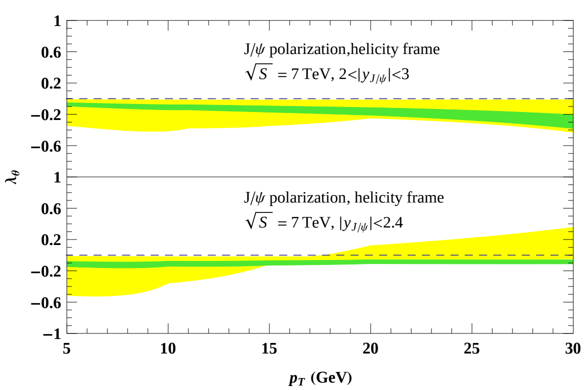

FIG. 4: (color online) NLO predictions of the J/ψ polarization observable λ_θ at the LHC. The uncertainty is shown by large yellow bands when varying the CO LDME $\langle\mathcal{O}(^1S_0^{[8]})\rangle$. The bounds of $\lambda_\theta = 0$ in yellow bands correspond to CO LDMEs in the third row of Tab.I, while the other bounds correspond to the second row of Tab.I. The small green bands are the predictions using the CO LDMEs in the first row of Tab.I.

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Note added. When this letter was being prepared, another preprint [21] on the same issue appeared. The essential difference is that they have a negative $\langle\mathcal{O}(^3P_0^{[8]})\rangle$ based on a global fit[20], and give a significant transverse polarization prediction, but our fit leads to a positive $\langle\mathcal{O}(^3P_0^{[8]})\rangle$, which is consistent with observed cross sections in a wide p_T region (7-70 GeV) at the LHC and results in mainly unpolarized J/ψ.

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