Hadroproduction and Polarization of Charmonium

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ABSTRACT

In the limit of heavy quark mass, the production cross section and polarization of quarkonia can be calculated in perturbative QCD. We study the $p_\perp$-averaged production of charmonium states in πN collisions at fixed target energies. The data on the relative production rates of J/ψ and χ_J is found to disagree with leading twist QCD. The polarization of the J/ψ indicates that the discrepancy is not due to poorly known parton distributions nor to the size of higher order effects (K-factors). Rather, the disagreement suggests important higher twist corrections, as has been surmised earlier from the nuclear target A-dependence of the production cross section.

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1 Introduction

Quarkonium bound states formed by heavy quark-antiquark pairs are small nonrelativistic systems, whose production and decay properties are expected to be governed by perturbative QCD. The extensive data available on the inclusive decays of many charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) states has been compared with detailed perturbative calculations. The overall agreement between theory and experiment is reasonably good, taking into account the moderate mass scale [1, 2, 3, 4]. This work has led to self-consistent values of the size of the quarkonium wave function near the origin.

Assuming, then, that we understand the decay of the quarkonium states to perturbative gluon and light-quark final states, we can turn the reaction around and consider the photoproduction and hadroproduction of quarkonia. Thus quarkonium production becomes a probe of the production mechanism of color-singlet heavy quark pairs. This is analogous to the dynamics of lepton pair hadroproduction, where the main production mechanism (at lowest order) has been identified as the Drell-Yan hard fusion subprocess $q\bar{q} \rightarrow \gamma^*$. Quarkonium production can offer new insights into gluon fusion mechanisms; for example, the J/ψ and χ_1 couple to states with more than two light partons, such as ggg or $q\bar{q}g$. At leading twist, *i.e.*, to leading order in $1/m_Q$, quarkonium production proceeds through the collision of only two partons, one from the projectile and one from the target. Hence an extra gluon or quark must be emitted in the leading twist production of J/ψ and χ_1. However, at large values of the quarkonium momentum fraction x_F, it becomes advantageous for two or more collinear partons from either the projectile or target to participate in the reaction. Such processes are higher twist, since their rate is suppressed relative to ordinary fusion reactions by powers of Λ_{QCD}/m_Q where Λ_{QCD} is the characteristic transverse momentum in the incident hadron wavefunction. Nevertheless, despite the extra powers of $1/m_Q$, the multiparton processes can become dominant at $(1 - x_F) < \mathcal{O}(\Lambda_{QCD}^2/m_Q^2)$ since they are efficient in converting the incident hadron momentum into high x_F quarkonia [5].

2

In leading twist QCD the production of the J/ψ at low transverse momentum occurs both 'directly' from the gluon fusion subprocess $gg \to J/\psi + g$ and indirectly via the production of χ_1 and χ_2 states[1]. These states have sizable decay branching fractions $\chi_{1,2} \to J/\psi + \gamma$ of 27% and 13%, respectively. In spite of its relatively small branching ratio, the χ_2 state is expected to give an important contribution to the total yield of J/ψ's at leading twist, since $gg \to \chi_2$ is of lower order in α_s compared to the competing processes. Early comparisons [7, 8, 9, 10] with the total J/ψ cross section data indicated rough agreement with the model predictions. Nevertheless, the cross sections for direct J/ψ and χ_1 production were predicted [11] to be too low compared to the data [12, 13, 14, 15, 16].

More recent E705 and E672 data [17, 18] on the production fractions of the various charmonium states have confirmed that there is a clear discrepancy with the leading twist QCD prediction. The leading twist calculations which we present in this paper show that the predicted ratio of direct J/ψ production in πN collisions compared to the χ_2 production is too low by a factor of about 3. In addition, the ratio of χ_1 production to χ_2 production is too low by a factor of 10. A similar conclusion has been reached in [3], where possible explanations in terms of uncertainties in the partonic cross sections (very different K-factors for the various processes) or unconventional pion parton distributions are discussed. Less data is available for proton-induced charmonium production, but a discrepancy between leading twist QCD and experiment appears likely also in that case.

The wealth of data from the NA3 experiment at CERN [19] and the Chicago-Iowa-Princeton [20] and E537 experiments [21] at FermiLab on the angular distribution of the muons in the decay $J/\psi \to \mu^+ \mu^-$ provides an even more sensitive discriminant of different production mechanisms [22, 23, 24, 25, 26, 27, 28].

The polarization of the $c\bar{c}$, and hence that of the charmonium bound state [23], can at leading twist be calculated from perturbative QCD. Furthermore, in the heavy quark limit, the radiative transition $\chi_J \to J/\psi + \gamma$ preserves the quark spins, i.e., it is an electric dipole transition. Hence the polarization also of indirectly produced J/ψ's

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[1]At high transverse momentum, one also has to take into account production through quark and gluon fragmentation [6].

can be calculated. We find that even if the relative production rates of the J/ψ, χ_1 and χ_2 are adjusted (using K-factors) to agree with the data, the J/ψ polarization data is still not reproduced.

We shall argue that a possible explanation for the underestimate of the J/ψ and χ_1 cross sections is that more than one parton from either the projectile or target participates in the collision, so that no additional gluon needs to be emitted. Similar higher twist effects are known to become important at high x_F in lepton pair production [29, 30, 31, 32]. In Ref. [30] it is shown that higher twist contributions can explain the large azimuthal $\cos\phi$ and $\cos 2\phi$ correlations seen in the $\pi N \rightarrow \mu^+\mu^-$ data. There are also previous indications from the non-factorizing anomalous nuclear target dependence of the J/ψ cross section [33, 19, 34, 35, 36] that higher twist effects are considerably larger in J/ψ production than in lepton pair production, and that they persist down to low x_F.

2 Production rates of ψ and χ_J states at leading twist

In this section we calculate J/ψ production in πN interactions at leading twist and to lowest order[2] in α_s. Higher order corrections in α_s and relativistic corrections to the charmonium bound states are unlikely to change our qualitative conclusions at moderate x_F. Contributions from direct J/ψ production, as well as from indirect production via χ_1 and χ_2 decays, are included. Due to the small branching fraction $\chi_0 \rightarrow J/\psi + \gamma$ of 0.7%, the contribution from χ_0 to J/ψ production is expected (and observed) to be negligible. Decays from the radially excited 2^3S_1 state, $\psi' \rightarrow J/\psi + X$, contribute to the total J/ψ rate at the few per cent level and also will be ignored here.

Since the ψ' is formed directly, its production allows an important cross check on the use of charmonium states to study the production mechanism. At high energies, the charmonium bound state forms long after the production of the compact $c\bar{c}$ pair (the formation time $\tau_{\text{form}} \sim 2E_{\text{lab}}/\Delta M^2$). Thus the ratio of ψ' to direct J/ψ produc-

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[2]Thus we do not include subprocesses like $qg \rightarrow \chi_2 q$ (which is subleading to $gg \rightarrow \chi_2$).

4

tion can depend only on the relative magnitude of their wave functions at the origin. More precisely (see, e.g., [3]),

$$\frac{\sigma(\psi')}{\sigma_{\mathrm{dir}}(J/\psi)} \simeq \frac{\Gamma(\psi' \to e^+ e^-)}{\Gamma(J/\psi \to e^+ e^-)} \frac{M^3_{J/\psi}}{M^3_{\psi'}} \simeq 0.24 \pm 0.03 \qquad (1)$$

where $\sigma_{\mathrm{dir}}(J/\psi)$ is the cross section for direct production of the J/ψ. The ratio (1) should hold for all beams and targets, independent of the size of the higher twist corrections in producing the pointlike $c\bar{c}$ state. The energy should be large enough for the bound state to form outside the target. The available data is indeed compatible with (1). In particular, the E705 value [17] is about 0.24 (see Table 1). The anomalous nuclear target A-dependence observed for the J/ψ is also seen for the ψ' [36], so that the ratio (1) is indeed independent of A.

	$\sigma(\psi')$ [nb]	$\sigma_{\mathrm{dir}}(J/\psi)$[nb]	$\sigma(\psi')/\sigma_{\mathrm{dir}}(J/\psi)$
π^+	22 ± 5	97 ± 14	0.23 ± 0.07
π^-	25 ± 4	102 ± 14	0.25 ± 0.05
p	20 ± 3	89 ± 12	0.23 ± 0.05

Table 1: Production cross sections for ψ', direct J/ψ and their ratio in $\pi^+ N$, $\pi^- N$ and pN collisions. The data are from Ref. [17].

The $\pi N \to \chi_2 + X$ production cross section to lowest order and twist is

$$\sigma(\pi N \to \chi_2 + X; \ x_F > 0) = \tau \int_{\sqrt{\tau}}^1 \frac{dx_1}{x_1} F_{g/\pi}(x_1) F_{g/N}(\tau/x_1) \sigma_0(gg \to \chi_2) \qquad (2)$$

where $\tau = M^2_{\chi_2}/s$ and the quantity $\sigma_0(gg \to \chi_2) = 16\pi^2 \alpha_s^2 |R'_P(0)|^2/M^7_{\chi_2}$ [10]. We restrict the χ_2 momentum range to the forward CM hemisphere ($x_F > 0$) in accordance with the available data.

The direct $\pi N \to J/\psi + X$ cross section is similarly given by

$$\begin{aligned} \sigma(\pi N \to J/\psi + X; \ x_F > 0) &= \int_\tau^1 dx_1 \int_{\tau/x_1}^1 dx_2 \int_{\hat{t}_{\min}}^0 d\hat{t} F_{g/\pi}(x_1) F_{g/N}(x_2) \\ &\times \frac{d\sigma}{d\hat{t}}(gg \to J/\psi + g) \end{aligned} \qquad (3)$$

where $\hat{t}$ is the invariant momentum transfer in the subprocess, and

$$\hat{t}_{\min} = \max\left(\frac{x_2 M^2_{J/\psi} - x_1 \hat{s}}{x_1 + x_2}, M^2_{J/\psi} - \hat{s} \right). \qquad (4)$$

Eq. (3) also applies to the $\pi N \to \chi_1 + X$ reaction, in which case a sum over the relevant subprocesses $gg \to \chi_1 g$, $g\bar{q} \to \chi_1 \bar{q}$, $gq \to \chi_1 q$ and $q\bar{q} \to \chi_1 g$ is necessary. The differential cross sections $d\sigma/d\hat{t}$ for all subprocesses are given in [10, 37]. In Table 2 we compare the χ_2 production cross section and the relative rates of direct J/ψ and χ_1 production at $E_{lab} = 300$ GeV with the data of E705 and WA11 on $\pi^- N$ collisions at $E_{lab} = 300$ GeV and 185 GeV [14, 17]. We use the parton distributions of Ref. [38, 39] evaluated at $Q^2 = M^2$, where M is the mass of the charmonium state in question. We take $\alpha_s = 0.26$ for all states and use $|R_S(0)|^2 = 0.7$ GeV^3, $|R'_P(0)/M|^2 = 0.006$ GeV^3 [40].

	$\sigma(\chi_2)$ [nb]	$\sigma_{\mathrm{dir}}(J/\psi)/\sigma(\chi_2)$	$\sigma(\chi_1)/\sigma(\chi_2)$
Experiment	$188 \pm 30 \pm 21$	$0.54 \pm 0.11 \pm 0.10$	$0.70 \pm 0.15 \pm 0.12$
Theory	78	0.17	0.067

Table 2: Production cross sections for χ_1, χ_2 and directly produced J/ψ in $\pi^- N$ collisions at 300 GeV. The data from Ref. [14, 17] include measurements at 185 and 300 GeV.

The χ_2 production rate in QCD agrees with the data within a 'K-factor' of order 2 to 3. This is within the theoretical uncertainties arising from the J/ψ and χ wavefunctions, higher order corrections, parton distributions, and the renormalization scale. A similar factor is found between the lowest-order QCD calculation and the data on lepton pair production [41, 42]. On the other hand, Table 2 shows a considerable discrepancy between the calculated and measured relative production rates of direct J/ψ and χ_1 compared to χ_2 production. A priori we would expect the K-factors to be roughly similar for all three processes. It should be noted that there is a kinematic region in the J/ψ and χ_1 processes where the emitted parton is soft (in the rest frame of the charmonium), and where perturbation theory could fail. However, the contribution from this region is numerically not important (there is actually no infrared divergence). Hence one cannot hope to boost the cross section significantly by multiplying the soft parton contribution by any reasonable factor. Moreover, the same soft parton region exists in charmonium decays, where analogous disagreements with data are absent. It should also be noted that the contribution to

6

χ_1 production from the $q\bar{q} \to \chi_1 + g$ subprocess is apparently singular at $\hat{s} = M_{\chi_1}^2$ due to a breakdown of the non-relativistic approximation of the bound state [11]. The divergence is cancelled once one takes into account higher Fock states [4]. In agreement with Ref. [3, 43] we find that the cross section is insensitive to the value of the cutoff parameter excluding the soft gluon region.

We conclude that leading twist QCD appears to be in conflict with the observed rate of direct J/ψ and χ_1 production. Although in Table 2 we only compared our calculation with the E705 and WA11 $\pi^- N$ data, this comparison is representative of the overall situation (for a recent comprehensive review see [3]).

3   Polarization of the J/ψ

The polarization of the J/ψ is determined by the angular distribution of its decay muons in the J/ψ rest frame. By rotational symmetry and parity, the angular distribution of massless muons, integrated over the azimuthal angle, has the form

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \lambda\cos^2\theta \qquad (5)$$

where we take θ to be the angle between the μ^+ and the projectile direction (*i.e.*, we use the Gottfried–Jackson frame). The parameter λ can be calculated from the $c\bar{c}$ production amplitude and the electric dipole approximation of radiative χ decays. Earlier calculations of the polarization in hadroproduction [22, 24, 25] were based on general effective couplings of the quarkonia and partons rather than the perturbative-QCD matrix elements which we shall use.

The electric dipole approximation of the radiative decay $\chi_J \to \psi\gamma$ is exact in the heavy quark limit, *i.e.*, when terms of $\mathcal{O}(E_\gamma/m_c)$ are neglected. As a consequence, the heavy quark spins are conserved in the decay, while the orbital angular momentum changes. This spin conservation may also be derived from Heavy Quark Symmetry [44]. The validity of the electric dipole approximation for χ_J radiative decays has been verified experimentally [45].

The amplitude for the χ_2 production subprocess $g(\mu_1)g(\mu_2) \to c\bar{c} \to \chi_2(J_z)$ is, following the notation of Ref. [46],

$$A(J_z = \pm 2) = 4\alpha_s R'_P(0)\sqrt{\frac{\pi}{M^3}}\, e^{\mp 2i\phi} \cdot$$
$$\times [1 \mp (\mu_2 - \mu_1)\cos\vartheta - \mu_1\mu_2\cos^2\vartheta - \delta_{\mu_1\mu_2}\sin^2\vartheta] \qquad (6)$$

$$A(J_z = \pm 1) = 4\alpha_s R'_P(0)\sqrt{\frac{\pi}{M^3}}\sin\vartheta\, e^{\mp i\phi}$$
$$\times [\mu_1 - \mu_2 \mp 2\mu_1\mu_2\cos\vartheta \pm 2\delta_{\mu_1\mu_2}\cos\vartheta] \qquad (7)$$

$$A(J_z = 0) = 4\alpha_s R'_P(0)\sqrt{\frac{\pi}{M^3}}\sqrt{6}\,\delta_{\mu_1,-\mu_2}\sin^2\vartheta \qquad (8)$$

where ϑ, ϕ are the polar and azimuthal angles of the beam gluon in the Gottfried–Jackson frame; $\vartheta = 0$ if the transverse momenta of the incoming gluons are neglected. In this case, as expected for physical, transversely polarized gluons with $\mu_{1,2} = \pm 1$, the amplitude for χ_2 production with $J_z = \mu_1 - \mu_2 = \pm 1$ vanishes. Surprisingly, the amplitude for $J_z = 0$ also vanishes when $\vartheta = 0$. Hence the χ_2 is at lowest order produced only with $J_z = \pm 2$. In this polarization state the spin and orbital angular momenta of its constituent charm quarks are aligned, $S_z = L_z = \pm 1$. Since S_z is conserved in the radiative decay $\chi_2 \to J/\psi + \gamma$, it follows that $J_z(J/\psi) = S_z = \pm 1$ ($L = 0$ for the J/ψ). Thus the J/ψ's produced via χ_2 decay are transversely polarized, i.e., $\lambda = 1$ in the angular distribution (5). This result is exact if both the photon recoil and the intrinsic transverse momenta of the incoming partons are neglected. Smearing of the beam parton's transverse momentum distribution by a Gaussian function $\exp[-(k_\perp/500\ \text{MeV})^2]$ would reduce λ to $\simeq 0.85$.

From the $gg \to J/\psi + g$ amplitude we find for direct J/ψ production, $\pi N \to J/\psi + X \to \mu^+\mu^- + X$,

$$\frac{1}{B_{\mu\mu}}\frac{d\sigma}{dx_F d\cos\theta} = \frac{3}{64\pi}\int \frac{dx_1 dx_2}{(x_1+x_2)\hat{s}} F_{g/\pi}(x_1) F_{g/N}(x_2)$$
$$\times \left[\varrho_{11} + \varrho_{00} + (\varrho_{11} - \varrho_{00})\cos^2\theta\right] \qquad (9)$$

where $B_{\mu\mu}$ is the $J/\psi \to \mu^+\mu^-$ branching fraction, $x_F = 2p_\psi^z/\sqrt{s}$ is the longitudinal-momentum fraction of the J/ψ, and θ is the muon decay angle of Eq. (5). The density matrix elements $\varrho_{11}, \varrho_{00}$ are given in the Appendix.

For the $\pi N \to \chi_1 + X \to J/\psi + \gamma + X \to \mu^+\mu^- + \gamma + X$ production process we obtain similarly

$$\frac{1}{B_{\mu\mu}}\frac{d\sigma}{dx_F d\cos\theta} = \frac{3}{128\pi}\mathrm{Br}(\chi_1 \to \psi\gamma)\sum_{ij}\int\frac{dx_1 dx_2}{(x_1+x_2)\hat{s}}F_{i/\pi}(x_1)F_{j/N}(x_2)$$
$$\times\left[\varrho_{00}^{ij} + 3\varrho_{11}^{ij} + (\varrho_{00}^{ij} - \varrho_{11}^{ij})\cos^2\theta\right], \tag{10}$$

where the density matrix elements for $ij = gg$, gq, $g\bar{q}$ and $q\bar{q}$ scattering are again given in the Appendix.

In Fig. 1a we show the predicted values of the parameter λ of Eq. (5) in the Gottfried–Jackson frame as a function of x_F, for the direct J/ψ and the $\chi_{1,2} \to J/\psi + \gamma$ processes separately. Direct J/ψ production gives $\lambda \simeq 0.25$ in the moderate x_F region, whereas production via χ_1 results in $\lambda \simeq -0.15$. The dashed lines indicate the effect of a Gaussian smearing in the transverse momentum of the beam partons.

The $\lambda(x_F)$-distribution obtained when both the direct and indirect J/ψ production processes are taken into account is shown in Fig. 1b and compared with the Chicago–Iowa–Princeton [20] and E537 [21] data. Our QCD calculation gives $\lambda \simeq 0.5$ for $x_F \lesssim 0.6$, significantly different from the measured value $\lambda \simeq 0$. The E537 data gives $\lambda = 0.028 \pm 0.004$ for $x_F > 0$, to be compared with our calculated value $\lambda = 0.50$ in the same range.

The discrepancies between the calculated and measured values of λ are one further indication that the standard leading twist processes considered here are not adequate for explaining charmonium production. The J/ψ polarization is particularly sensitive to the production mechanisms and allows us to make further conclusions on the origin of the disagreements, including the above discrepancies in the relative production cross sections of J/ψ, χ_1 and χ_2. If these discrepancies arise from an incorrect relative normalization of the various subprocess contributions (e.g., due to higher order effects), then we would expect the J/ψ polarization to agree with data when the relative rates of the subprocesses are adjusted according to the measured cross sections of direct J/ψ, χ_1 and χ_2 production[3]. The lower curve in Fig. 1b shows the

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[3]In the case of Drell-Yan virtual photon production, it is known that higher order corrections do not change the γ^* polarization significantly [47], which makes it plausible to represent these corrections by a simple multiplicative factor that does not affect the polarization of the photon.

effect of multiplying the partial J/ψ cross sections with the required K-factors. The smearing effect is insignificant as shown by the dashed curve. The λ parameter is still predicted incorrectly over most of the x_F range.

A similar conclusion is reached (within somewhat larger experimental errors) if we compare our calculated value for the polarization of direct J/ψ production, shown in Fig. 1a, with the measured value of λ for ψ' production. In analogy to Eq. (1), the ψ' polarization data should agree with the polarization of directly produced J/ψ's, regardless of the production mechanism. Based on the angular distribution of the muons from $\psi' \rightarrow \mu^+ \mu^-$ decays in 253 GeV $\pi^- W$ collisions, Ref. [32] quotes $\lambda_{\psi'} = 0.02 \pm 0.14$ for $x_F > 0.25$, appreciably lower than our QCD values for direct J/ψ's shown in Fig. 1a.

4 Discussion

We have seen that the J/ψ and χ_1 hadroproduction cross sections in leading twist QCD are at considerable variance with the data, while the χ_2 cross section agrees with measurements within a reasonable K-factor of 2 to 3. On the other hand, the inclusive decays of the charmonium states based on the minimal perturbative final states (gg, ggg and $q\bar{q}g$) have been studied in detail using perturbation theory [1, 2, 3, 4], and appear to be fairly well understood. It is therefore improbable that the treatment of the $c\bar{c}$ binding should require large corrections. This conclusion is supported by the fact that the relative rate of ψ' and direct J/ψ production (Eq. (1)), which at high energies should be independent of the production mechanism, is in agreement with experiment.

In a leading twist description, an incorrect normalization of the charmonium production cross sections can arise from large higher order corrections or uncertainties in the parton distributions [3]. Even if the normalization is wrong by as much as a factor of 10, such a K-factor would not explain the J/ψ polarization data. Thus a more likely explanation of the discrepancy may be that there are important higher-twist contributions to the production of the J/ψ, ψ' and χ_1.

The direct J/ψ and χ_1 subprocesses require, at leading order and twist, the emis-

10

sion of a quark or gluon, *e.g.*, $gg \to J/\psi + g$. This implies a higher subenergy $\sqrt{\hat{s}}$ for these processes compared to that for the χ_2, which can be produced through simple gluon fusion, $gg \to \chi_2$. It is then plausible that a higher twist component which avoids the necessity for gluon emission is more significant for the J/ψ and the χ_1 than it is for the χ_2 (or for lepton pair production, $q\bar{q} \to \gamma^*$). If either the projectile or the target contributes *two* partons rather than one, no emission of a parton is required [48]: $(gg) + g \to J/\psi$. Similar production mechanisms are considered in Ref. [5].

Taking two partons from the same hadron is a higher twist process, and as such is suppressed by a factor of $\mathcal{O}(\Lambda_{QCD}^2/m_c^2)$. This factor describes the probability that the two partons are within a transverse distance of $\mathcal{O}(1/m_c)$, as required if both of them are to couple to the same $c\bar{c}$ pair. For the J/ψ and χ_1, this suppression is compensated by the fact that the subprocess energy $\hat{s}$ can be equal to the charmonium mass since no parton needs to be emitted. Finding two softer gluons in a hadron may also be more probable than the probability for one gluon carrying the full momentum.

In the $x_F \to 1$ limit, important higher twist effects are expected [29, 30, 31] and observed [32] also in the muon pair production process, $\pi N \to \mu^+\mu^- + X$. In effect, both valence quarks in the pion projectile must be involved in the reaction if the full momentum is to be delivered to the muons. The higher twist effect manifests itself in the angular distribution of the muons: the polarization of the virtual photon changes from transverse to longitudinal at large x_F. Thus the photon tends to carry the same helicity as the pion in the $x_F \to 1$ limit. It is natural to expect the higher twist effects to be similarly enhanced in J/ψ production at large x_F. As seen in Fig. 1b, the data does indeed show a remarkable turnover in the polarization of the J/ψ for $x_F \gtrsim 0.8$, with the fastest J/ψ's being longitudinally polarized. In contrast to the lepton pair production case, the evidence for higher twist effects persists, as we have seen, for J/ψ's produced even at lower momentum fractions.

It has recently been pointed out [49, 50] that there is also a large discrepancy between the leading twist QCD prediction and data for large $p_\perp$ charmonium production. At leading twist in $1/p_\perp^2$ and in $1/m_c^2$ the dominant source of "prompt" J/ψ's (*i.e.*, those not due to $B \to J/\psi + X$ decays) is predicted to be the radiative decays of P-wave charmonia, $\chi_c \to J/\psi + \gamma$. The J/ψ cross section obtained this

11

way is consistent with the data within a factor ~ 2. The actual χ_c production cross section has not yet been measured. However, the prediction for ψ' production (which cannot be produced via radiative decays) is too low by a factor ~ 30 when compared to the data. At the same time, the experimental ratio of the ψ' and total (prompt) J/ψ cross section is consistent with the universal ratio of Eq. (1). This suggests that a major part of the prompt high $p_\perp$ J/ψ's are produced directly, rather than via $\chi_c \rightarrow J/\psi + \gamma$ decays. Since the shape of the $p_\perp$-distribution of the measured J/ψ and ψ' cross sections is in agreement with the leading twist prediction [49, 50], the large higher twist corrections are likely to reside in the $g \rightarrow J/\psi$ and $c \rightarrow J/\psi$ fragmentation vertices, and thus be of $\mathcal{O}(1/m_c^2)$ rather than of $\mathcal{O}(1/p_\perp^2)$. This is consistent with our conclusions based on the low $p_\perp$ charmonium data. The much larger discrepancy at high $p_\perp$ is qualitatively expected since the high z region of the fragmentation is emphasized due to the "trigger bias" effect. As discussed above, the higher twist "intrinsic charm" mechanism is particularly important at high momentum fraction in either the projectile or fragmenting parton systems.

Additional independent evidence for higher twist effects in J/ψ production is also reflected in the nuclear target A-dependence of the cross section. In lepton pair production, the cross section is very closely linearly dependent on A (apart from a small deviation at the largest x_F [34]). J/ψ production, on the other hand, shows a nuclear suppression over the whole x_F range [36]. The suppression depends on x_F rather than on x_2, and it is thus possible to conclude [33] that QCD factorization must be broken, implying that the effect is due to higher twist terms.

Further theoretical work is needed to establish that the data on direct J/ψ and χ_1 production indeed can be described using a higher twist mechanism of the type discussed here. Experimentally, it is important to check whether the J/ψ's produced indirectly via χ_2 decay are transversely polarized. This would show that χ_2 production is dominantly leading twist, as we have argued. Better data on real or virtual photoproduction of the individual charmonium states would also add important information. So far, little is known about the relative size of direct and indirect J/ψ photoproduction, and the polarization measurements [51, 52] are too inaccurate to test theoretical predictions [23, 26, 27, 28].

In photoproduction one expects less higher twist effects associated with the projectile, since in the case of direct photon interactions only a single beam parton (the photon itself) is available. However, the target hadron can contribute two gluons. In the special case of diffractive J/ψ photoproduction [53], this is in fact expected to be the dominant reaction mechanism [54].

Acknowledgements

A   Density matrix elements

The density matrix elements for J/ψ production in the $gg \to J/\psi + g$ subprocess are defined as

$$\varrho_{\mu\mu'} \equiv \frac{1}{256} \sum_{\substack{\mu_1\mu_2\mu_3 \\ c_1c_2c_3}} A(g_1g_2 \to J/\psi(\mu) + g_3)A^*(g_1g_2 \to J/\psi(\mu') + g_3), \qquad (11)$$

where μ_i, c_i are the helicity and color of the gluon i, and the factor of $1/256$ comes from averaging over the initial helicities and colors. The diagonal matrix elements are found to be

$$\begin{aligned}
\varrho_{11} = & \frac{40\pi^2\alpha_s^3|R_S(0)|^2 M}{9[(s-M^2)(t-M^2)(u-M^2)]^2} \\
& \times \Big\{ s^2(s-M^2)^2 + t^2(t-M^2)^2 + u^2(u-M^2)^2 \\
& - 2M^2[\mathbf{k}_{1\perp}^2(s^2+t^2) + 2\mathbf{k}_{1\perp}\cdot\mathbf{k}_{2\perp}s^2 + \mathbf{k}_{2\perp}^2(s^2+u^2)] \Big\},
\end{aligned} \qquad (12)$$

$$\begin{aligned}
\varrho_{00} = & \frac{40\pi^2\alpha_s^3|R_S(0)|^2 M}{9[(s-M^2)(t-M^2)(u-M^2)]^2} \\
& \times \Big\{ s^2(s-M^2)^2 + t^2(t-M^2)^2 + u^2(u-M^2)^2 \\
& - 4M^2[k_{1z}^2(s^2+t^2) + 2k_{1z}k_{2z}s^2 + k_{2z}^2(s^2+u^2)] \Big\},
\end{aligned} \qquad (13)$$

13

where M is the J/ψ mass, s, t, u are the subprocess invariants (the carets being omitted for clarity), and $\mathbf{k}_{1,2}$ are the three-momenta of the beam and target partons in the Gottfried–Jackson frame.

In analogous notation, the diagonal density matrix elements for χ_1 production in $q\bar{q}$, gq and gg scattering are

$$\varrho_{11}^{q\bar{q}} = \frac{(64\pi)^2\alpha_s^3|R_P'(0)|^2}{9M(s - M^2)^4}\left[-t\mathbf{k}_{1\perp}^2 + (s - M^2)\mathbf{k}_{1\perp}\cdot\mathbf{k}_{2\perp} - u\mathbf{k}_{2\perp}^2 + tu\right], \tag{14}$$

$$\varrho_{00}^{q\bar{q}} = \frac{(64\pi)^2\alpha_s^3|R_P'(0)|^2}{9M(s - M^2)^4}\left[-2tk_{1z}^2 + 2(s - M^2)k_{1z}k_{2z} - 2uk_{2z}^2 + tu\right], \tag{15}$$

$$\varrho_{11}^{gq} = \frac{-3(64\pi)^2\alpha_s^3|R_P'(0)|^2}{72M(t - M^2)^4}\left[-s\mathbf{k}_{1\perp}^2 + (u - s)\mathbf{k}_{1\perp}\cdot\mathbf{k}_{2\perp} + su\right], \tag{16}$$

$$\varrho_{00}^{gq} = \frac{-3(64\pi)^2\alpha_s^3|R_P'(0)|^2}{72M(t - M^2)^4}\left[-2sk_{1z}^2 + 2(u - s)k_{1z}k_{2z} + su\right], \tag{17}$$

$$\begin{aligned}\varrho_{11}^{gg} = &\ \frac{96\pi^2\alpha_s^3|R_P'(0)|^2}{M^3(Q - M^2P)^4}\\ &\times P^2\left[M^2P^2(M^4 - 4P) - 2Q(M^8 - 5M^4P - P^2) - 15M^2Q^2\right]\\ &- \frac{1}{2}\varrho_{00}^{gg},\end{aligned} \tag{18}$$

$$\begin{aligned}\varrho_{00}^{gg} = &\ \frac{48\pi^2\alpha_s^3|R_P'(0)|^2}{Mstu[(s - M^2)(t - M^2)(u - M^2)]^4}\\ &\times \Big\{s^2(s - M^2)^2[k_{1z}g(s,t,u) + k_{2z}g(s,u,t)]^2\\ &+ u^2(u - M^2)^2[k_{1z}g(u,t,s) - (k_{1z} + k_{2z})g(u,s,t)]^2\\ &+ t^2(t - M^2)^2[(k_{1z} + k_{2z})g(t,s,u) - k_{2z}g(t,u,s)]^2\\ &+ 4M^2(k_{1x}k_{2y} - k_{2x}k_{1y})^2\\ &\times \left[s^2(s - M^2)^2f^2(s,t,u) + (s \leftrightarrow u) + (s \leftrightarrow t)\right]\Big\}.\end{aligned} \tag{19}$$

The density matrix elements ϱ^{qg} for the processes where a beam quark scatters off a target gluon are obtained by changing $\mathbf{k}_1 \leftrightarrow \mathbf{k}_2$ (and consequently $t \leftrightarrow u$) in ϱ^{gq}. The matrix elements for the $g\bar{q}$ and $\bar{q}g$ scattering processes are the same as for gq and qg, respectively. In deriving ϱ^{gg} we made use of the subprocess amplitudes given in Ref. [37]. The functions f, g, P and Q of the invariants are defined as

$$f(s,t,u) = (t - u)(st + tu + us - s^2), \tag{20}$$

$$g(s,t,u) = (s+t)[st(t-s) + su(u-s) + tu(t-u)], \qquad (21)$$

$$P = st + tu + us, \qquad (22)$$

$$Q = stu. \qquad (23)$$

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FIGURE CAPTION

Figure 1. Leading-twist predictions of the parameter λ in the decay angular distribution of J/ψ's produced in pion-nucleon collisions at $E_{\mathrm{lab}} = 300$ GeV, plotted as a function of x_F. *(a)* The three solid curves show the decay distributions of J/ψ's produced via radiative decays of the χ_2 and χ_1 states and "directly" in gluon fusion. The dashed curves show the effect of smearing the transverse momentum distribution of the beam parton by a Gaussian function $\exp\left[-(k_\perp/500 \text{ MeV})^2\right]$. *(b)* The combined decay distribution of all J/ψ's, including contributions from $\chi_{1,2}$ decays and direct production, is shown here. The lower curve shows the effect of adjusting the relative normalization of the different contributions to their measured values (see Table 2) by appropriate K-factors. The dashed curve shows the effect of transverse momentum smearing and K-factors adjustments . The data is from the Chicago–Iowa–Princeton (252-GeV πW collisions, Ref. [20]; full circles) and E537 (125-GeV πW collisions, Ref. [21]; open circles) experiments.
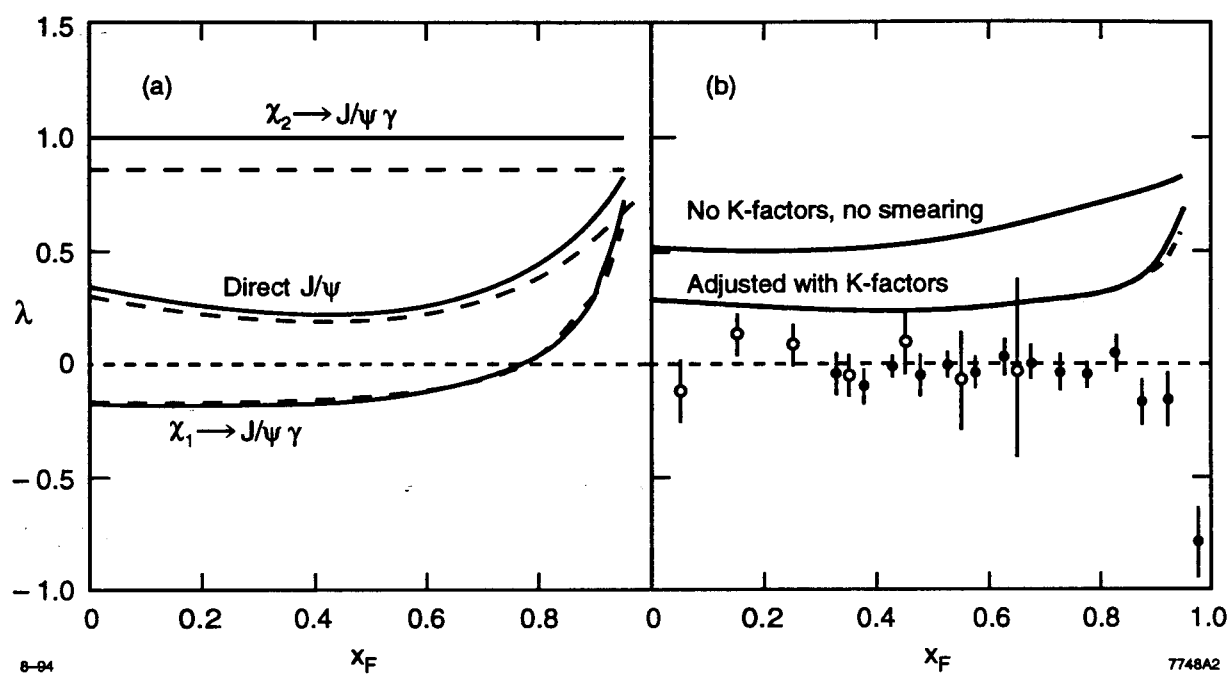
Fig. 1